

TSTE26 Powergrid and technology for renewable
production

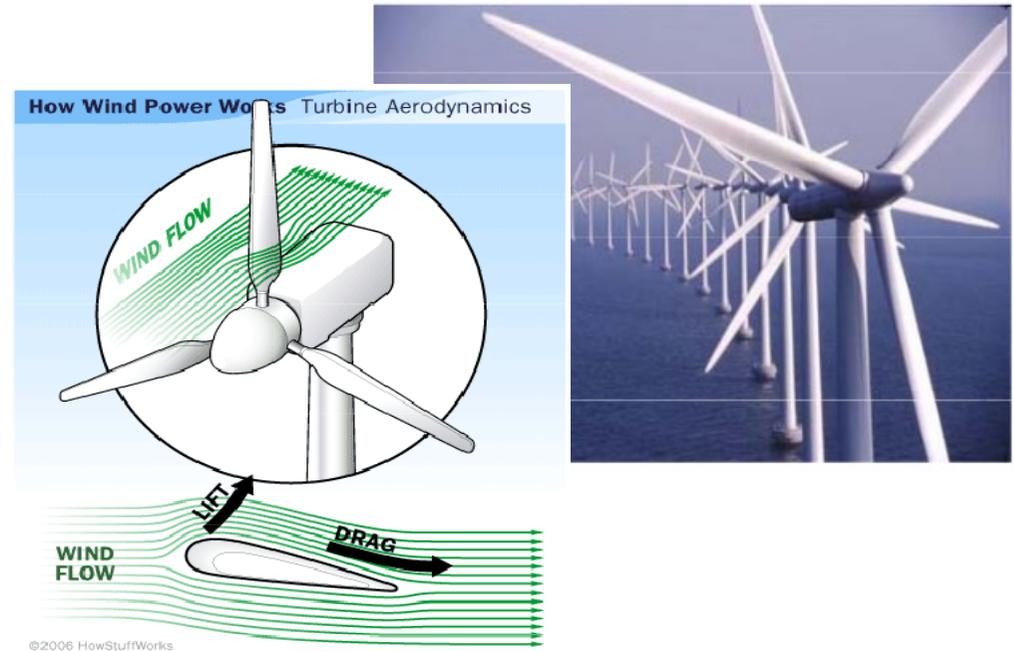
Lecture 6

Wind turbine grid connection

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FS/ISY

Understanding wind power

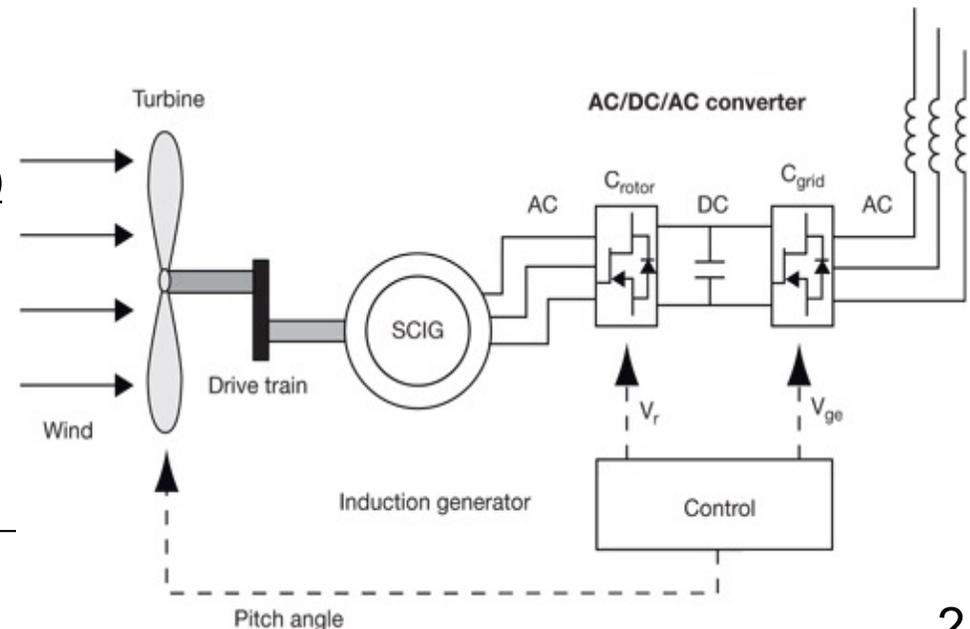
- Variable speed control
 - Synchronous generator,
 - Induction generator
 - Converter control
- Wind turbine type 1-5
- Grid connection
- Grid codes
- Power grid wind HVDC applications



Variable-speed turbine with a frequency converter

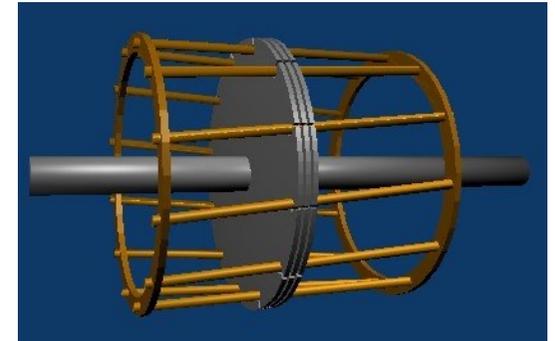
Literature (Available as eBooks at Liu library)

[Wind Power Integration: Connection and System Operational Aspects 2nd ed, Brendan Fox et al, IET 2014 \(Chapter 3-4\)](#)

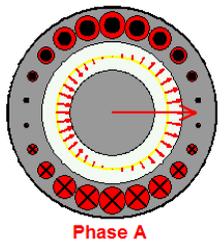


Type of wind generators

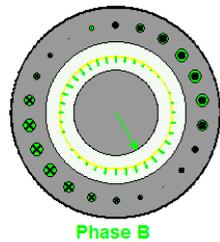
- Synchronous Generator
 - Wound rotor synchronous generator
 - Permanent magnet synchronous generator
- Asynchronous (Induction) Generator
 - Squirrel cage induction generator
 - Wound rotor induction generator
 - Optislip IG (variable rotor resistance)
 - Doubly-Fed IG (DFIG)



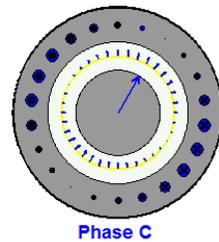
AC machines – Rotating magnetic field



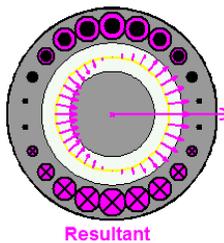
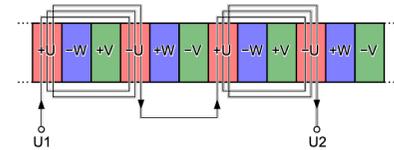
Phase A



Phase B

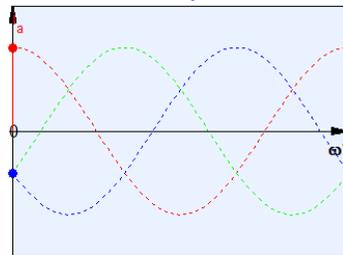


Phase C

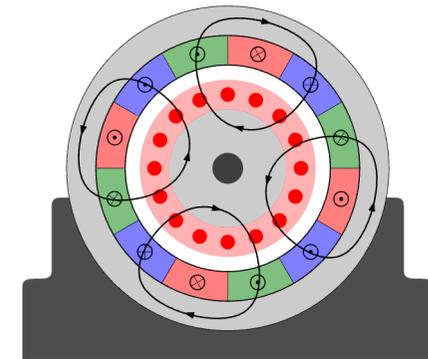
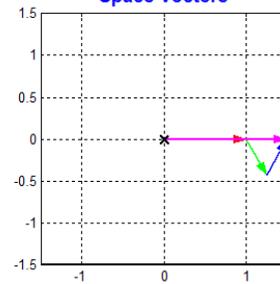


Resultant

Balanced three-phase currents

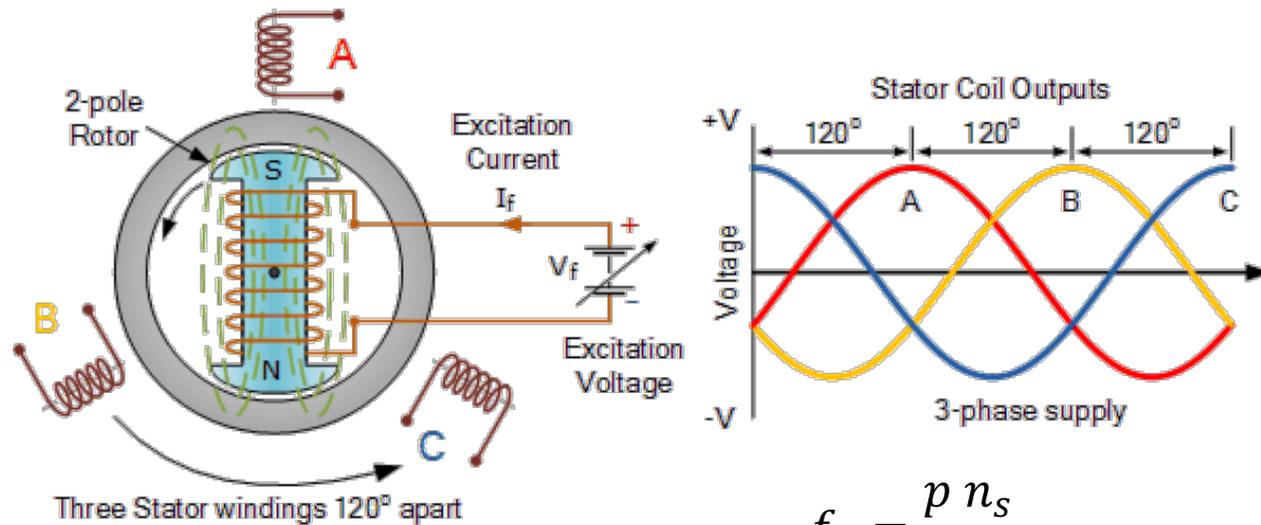


Space vectors



4-pole machine

The synchronous generator



$$f_s = \frac{p n_s}{2 \cdot 60}$$

Frequency [Hz]	50							
No of poles	2	4	6	8	12	24	36	48
Rotational speed [rpm]	3000	1500	1000	750	500	250	167	125

Rotational speed [rpm]	10							
No of poles	2	12	24	36	48	96	192	384
Frequency [Hz]	0.2	1.0	2.0	3	4	8	16	32

Synchronous Generator Reactive Power Capability

Wound rotor

synchronous generator

- Rotor current controls the magnetisation Ψ_R
- Internal voltage defined by magnetisation

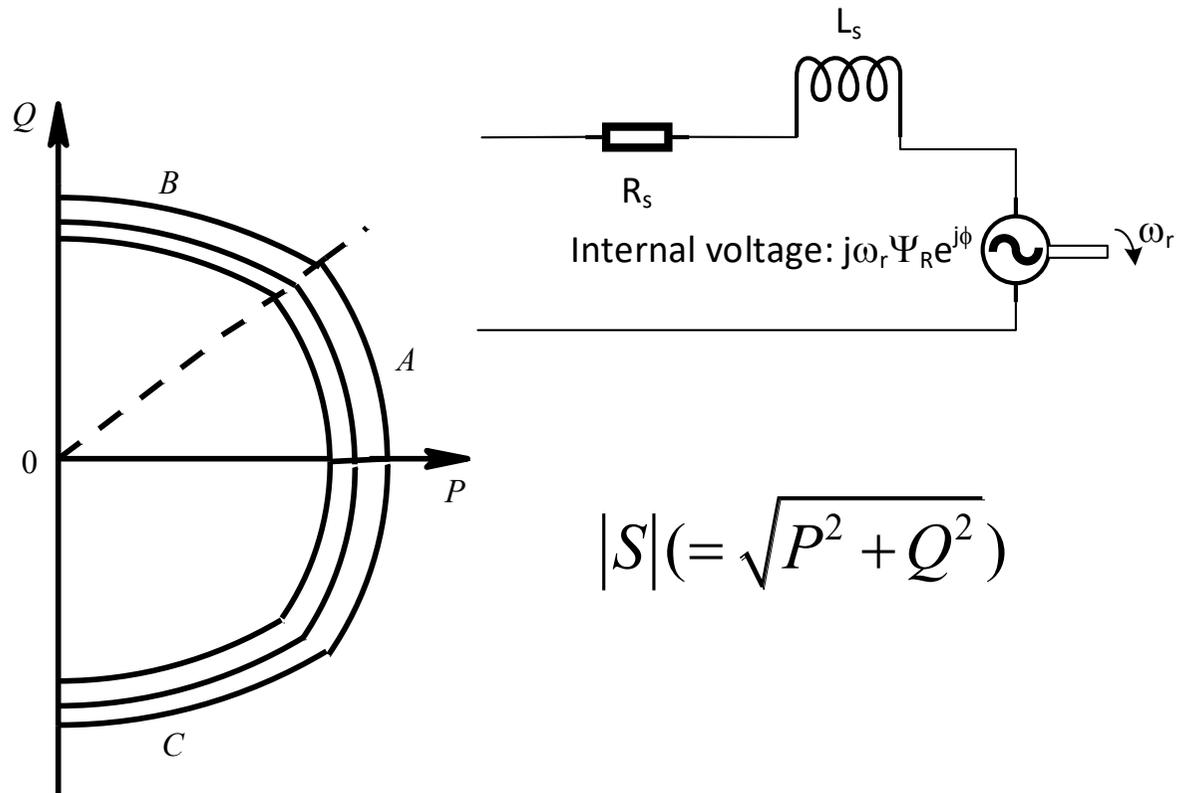
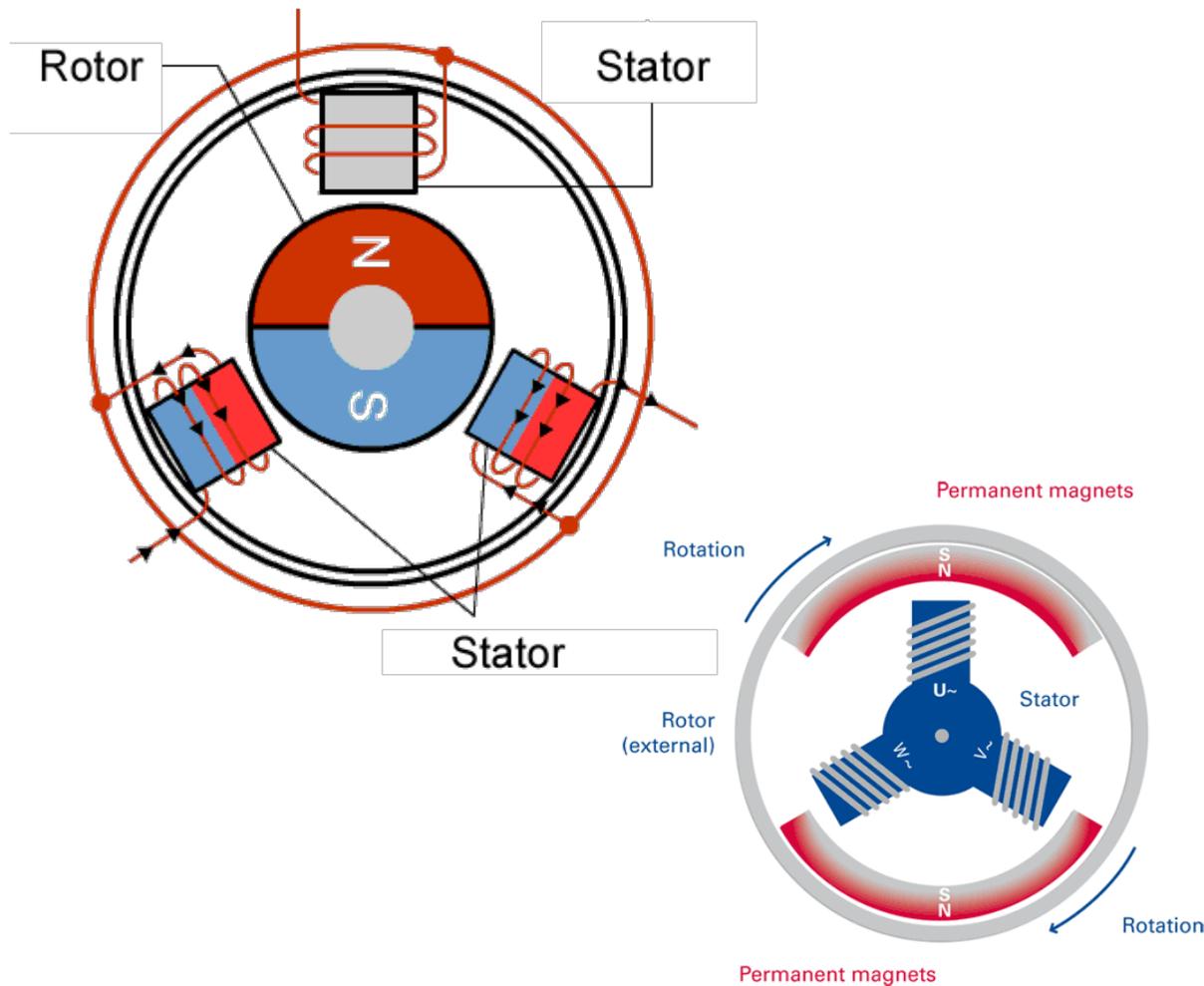


Fig. 10-5 Reactive power supply capability of synchronous generators.

Permanent magnet synchronous generator



- Robust design
- No slip rings as for wound rotor
- Used in direct drive wind turbines (no gear box) with high no of poles
- Large size and weight due to low speed

The induction machine

- Rotating transformer
- Stator field rotate at synchronous speed n_s : [rpm]

$$n_s = \frac{120f_s}{p}$$

(Grid frequency f_s)

Difference between rotor speed and stator synchronous speed (magnetic field):

- Slip, given in % of n_s

$$s = \frac{n_s - n_r}{n_s}$$

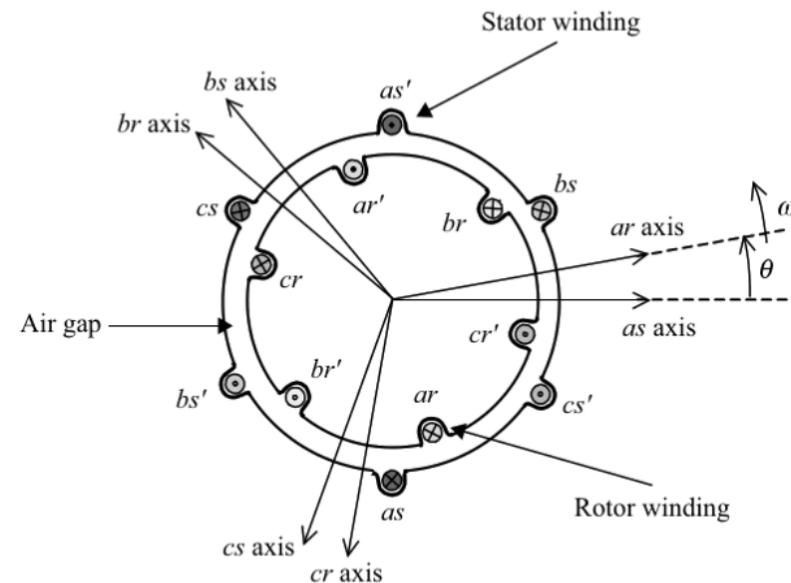
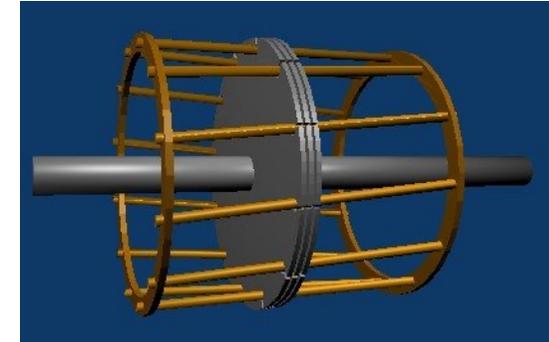


Figure 3.10 Schematic diagram of a three-phase induction machine (Kundur, 1994)

Rotating transformer principle

Induced voltage in rotor proportional to rate of change of flux. Thereby dependent on slip:

$$\text{rotor voltage} = sV_{r,max}$$

Stand still:

$$n_r = 0, s = 1$$

$$\text{rotor voltage} = V_{r,max}$$

Rotor at synchronous speed:

$$n_r = n_s, s = 0$$

$$\text{rotor voltage} = 0$$

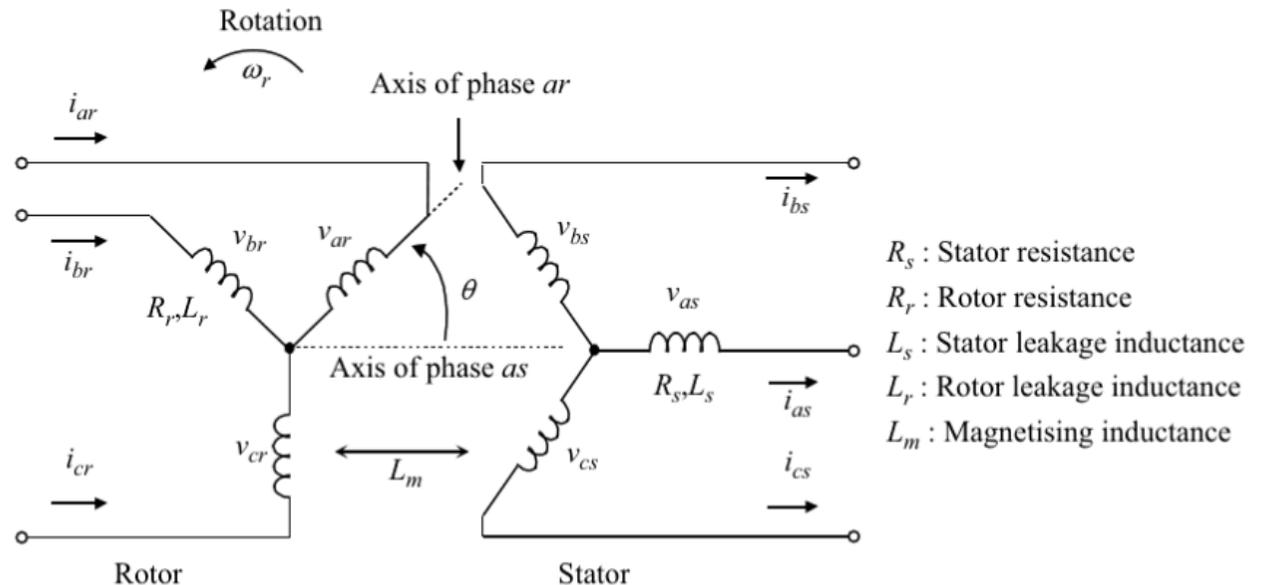


Figure 3.11 Stator and rotor electrical circuit of an induction machine (Kundur, 1994)

Equivalent circuit of induction machine

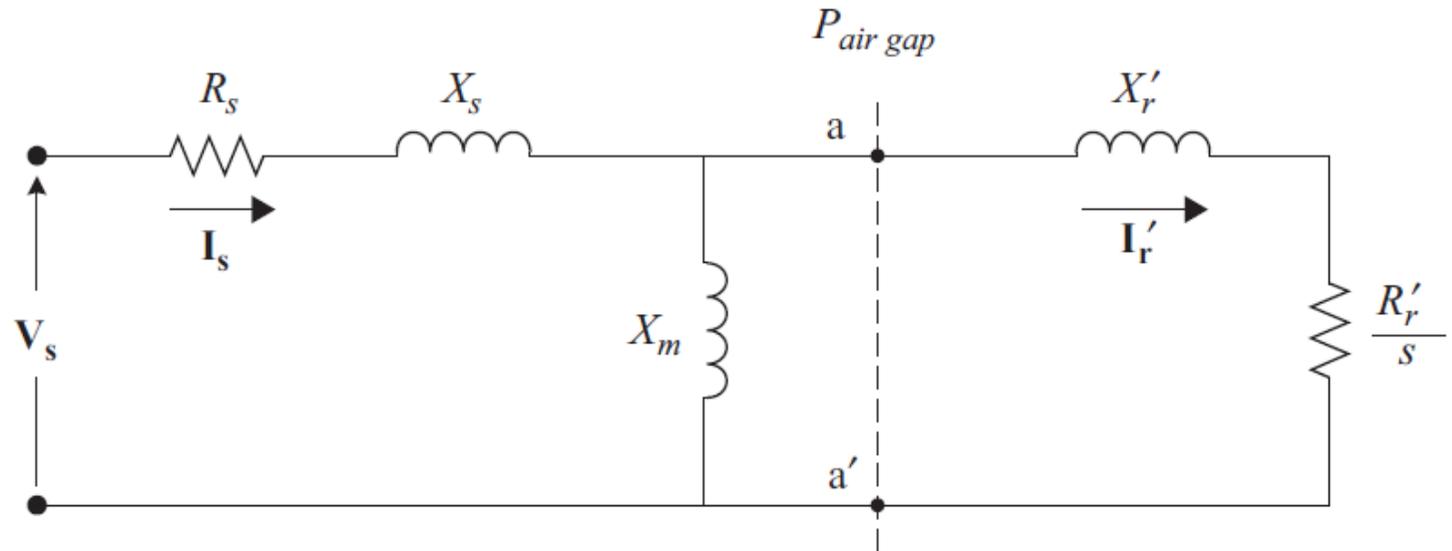
$$s = \frac{\omega_s - \omega_r}{\omega_s}$$

- Equivalent rotor with same frequency as stator.
- Actual rotor current with frequency $s\omega_s$

$$I_r = \frac{sV_r}{R_r + js\omega_s L_r}$$

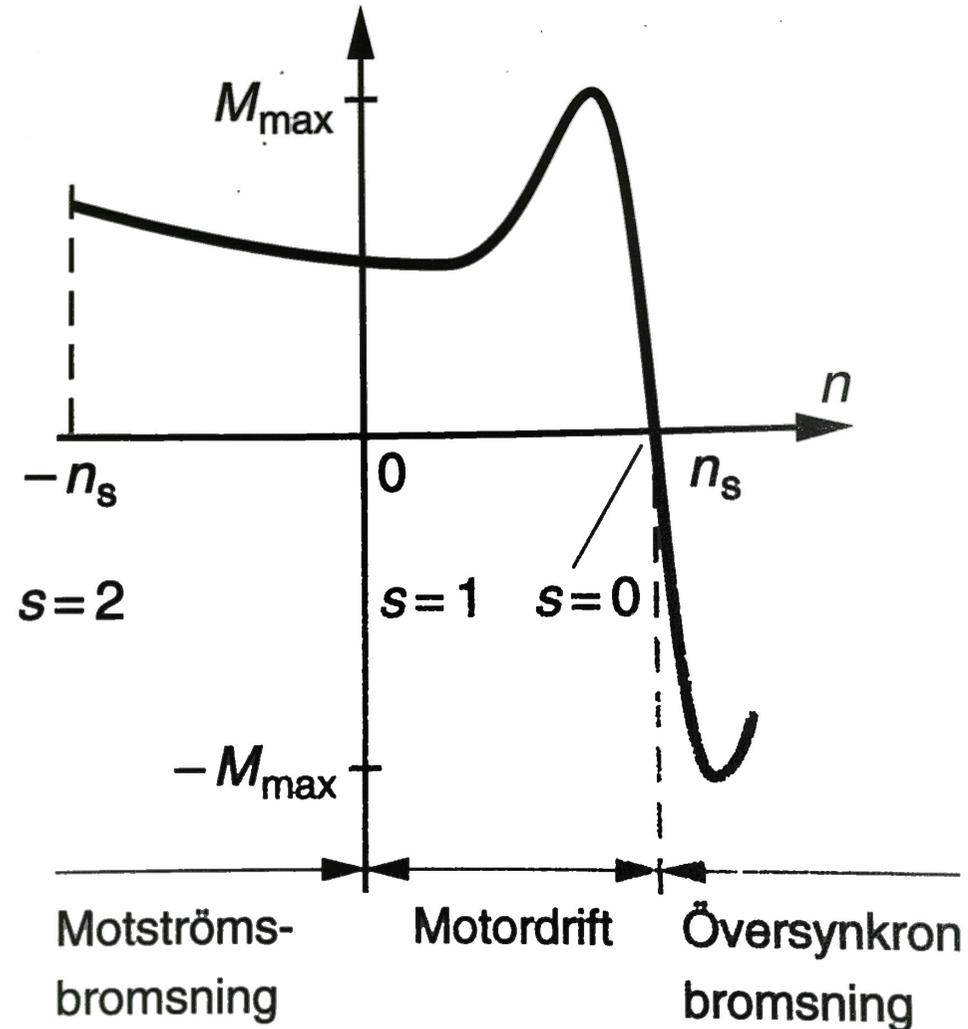
- Equivalent rotor current with frequency ω_s

$$I'_r = N \frac{V_r}{R'_r/s + jX'_r}$$



Torque characteristics, variable rotor resistance

$$s = \frac{n_s - n_r}{n_s}$$



Torque characteristics, variable rotor resistance

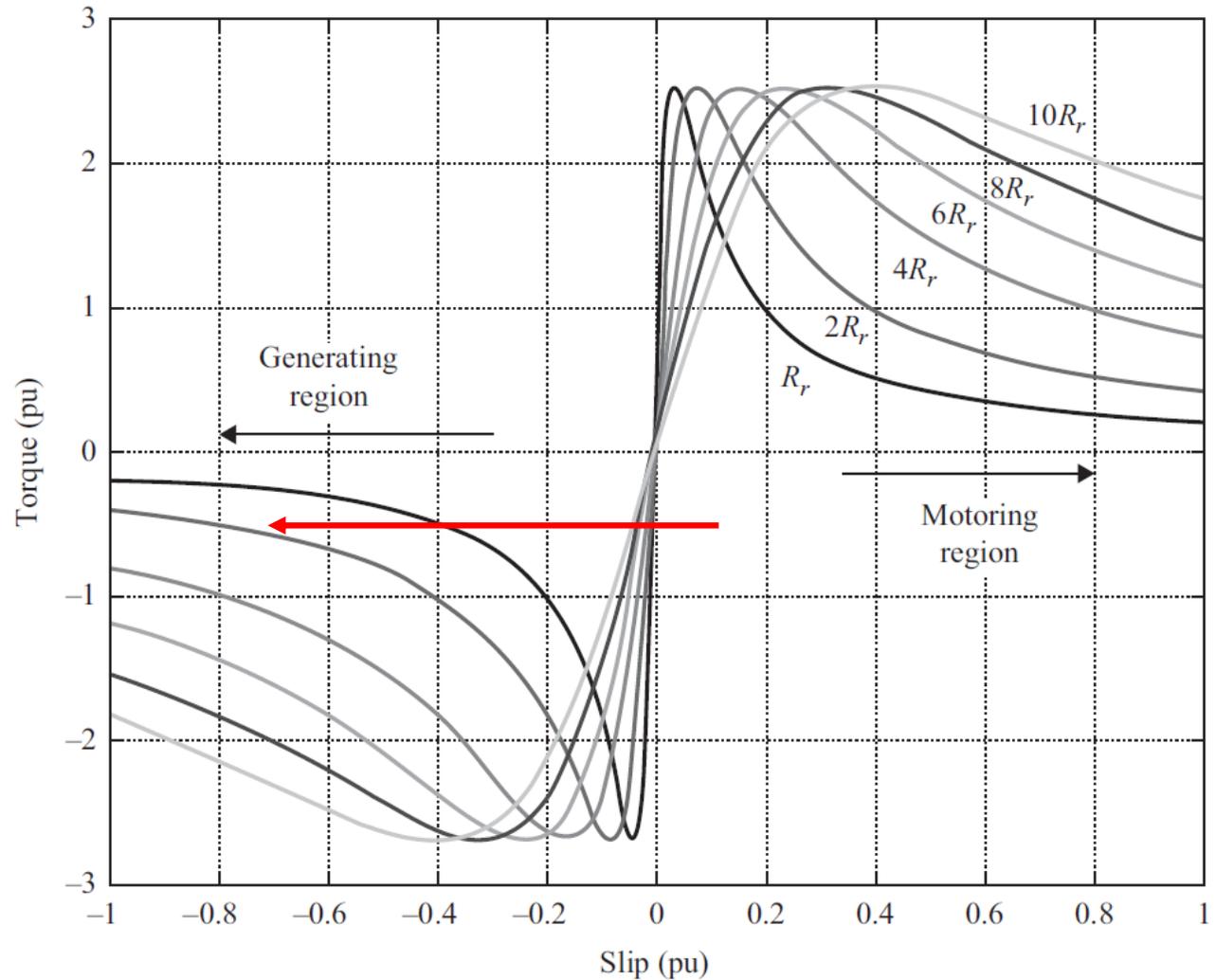
$$s = \frac{n_s - n_r}{n_s}$$

Variable rotor speed:

$$n_r = n_s(1-s)$$

$$s = -0.2: n_r = 1.2n_s$$

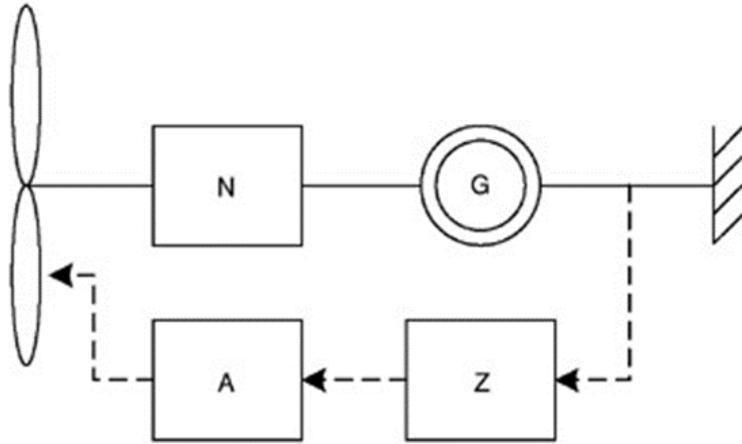
$$s = -0.4: n_r = 1.4n_s$$



Comparison wind turbine types

	Type 1	Type 2, Optislip	Type 3, DFIG	Type 4, Full conv	Type 5, torque conv
Variable speed	No	Partial	Yes	Yes	Yes
Power limitation	Stall	Pitch control	Pitch control	Pitch control	Pitch control
Size	<1 MW	1 – 2 MW	< 4 MW	3 – 8 MW	
Torque control	No	Yes	Yes	Yes	Yes
Fault ride through	No	No	Yes	Yes	

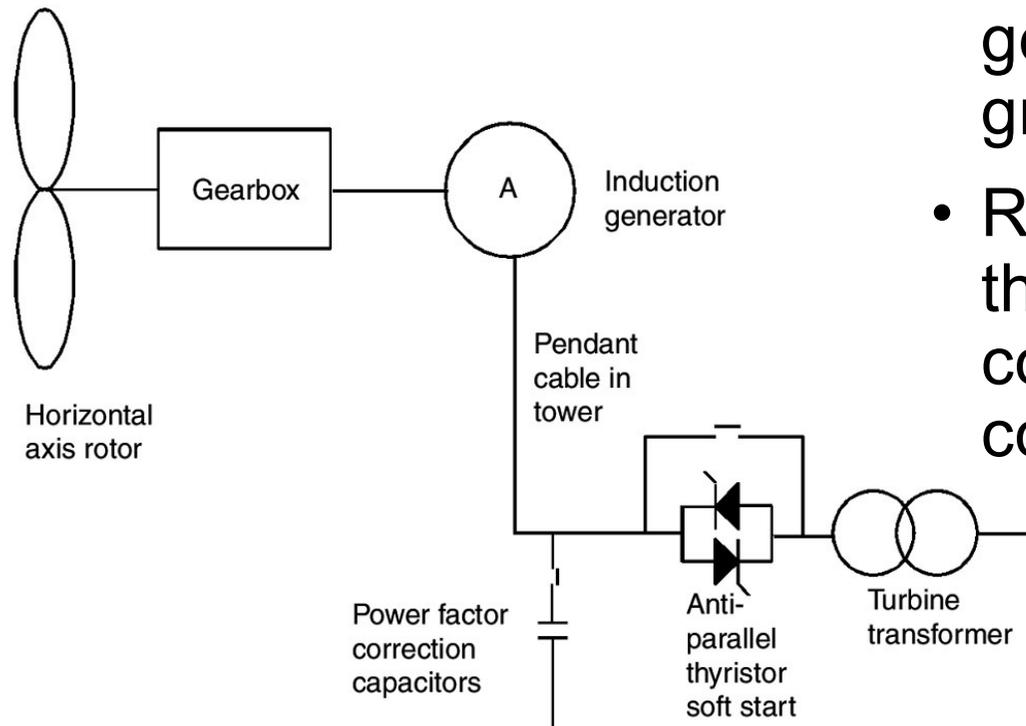
Type 1, Fixed speed turbine



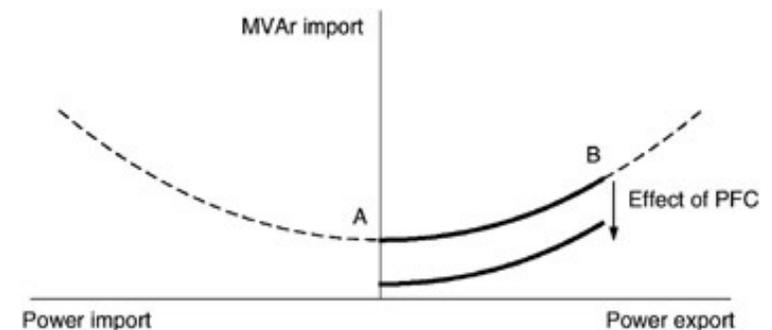
N: gearbox
G: generator
Z: control system
A: actuator

- Induction generator with squirrel cage induction generator

Direct grid connection

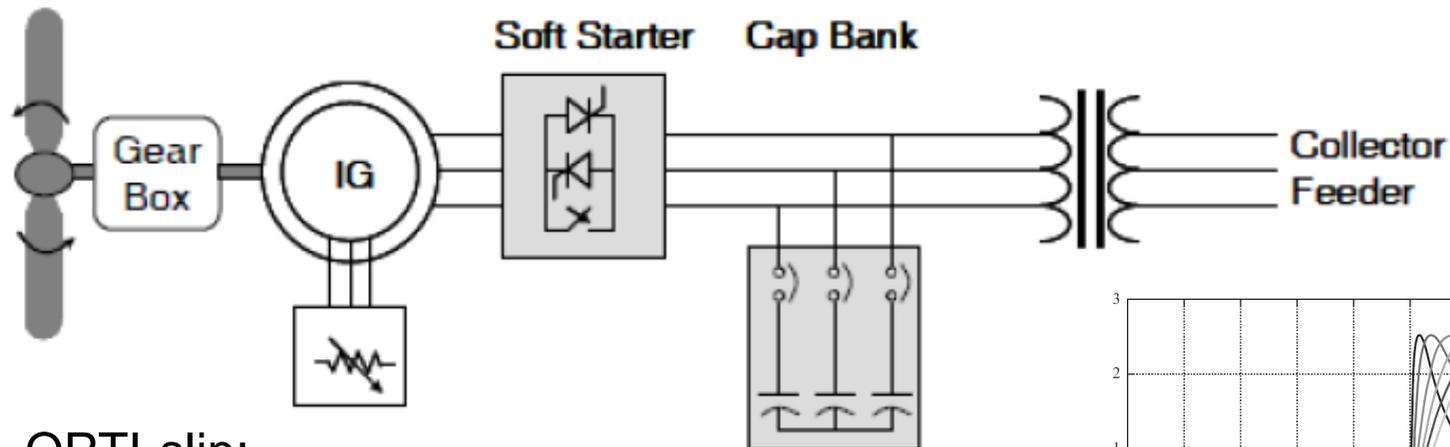


- Up-transformation from generator output (typ 690 V) to grid voltage level (typ 10-36 kV)
- Reactive power generation through capacitors to compensate reactive power consumption of generator

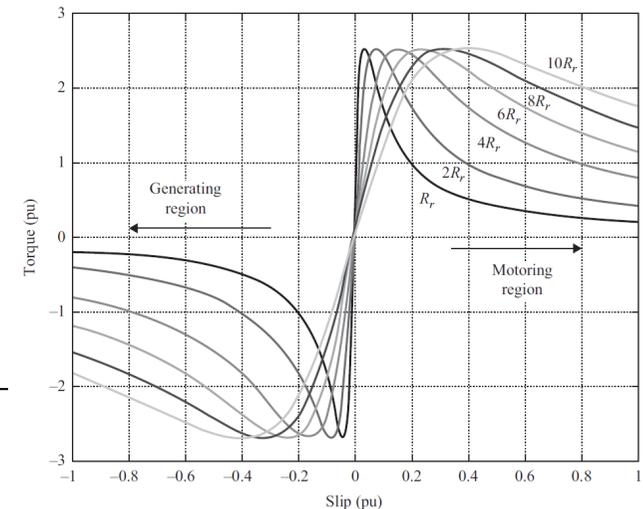


Type 2, limited variable speed

- Induction generator with variable rotor resistance

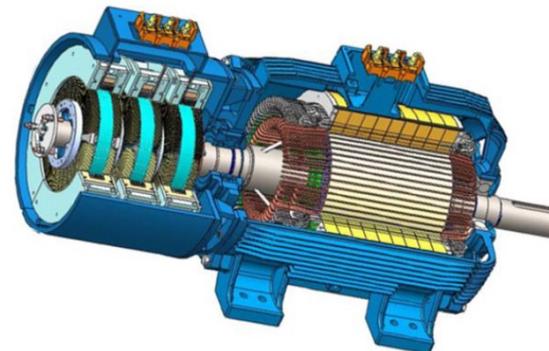
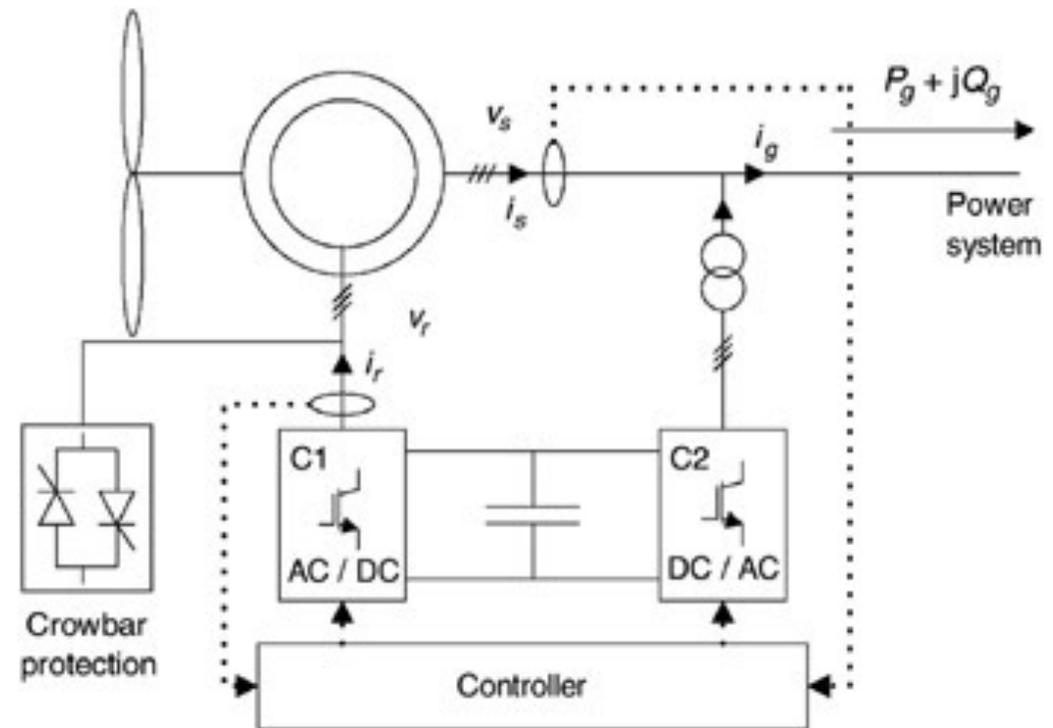


OPTI-slip:
Converter controlled rotor resistance
mounted in the rotor. Controlled via optical
link. No slip rings



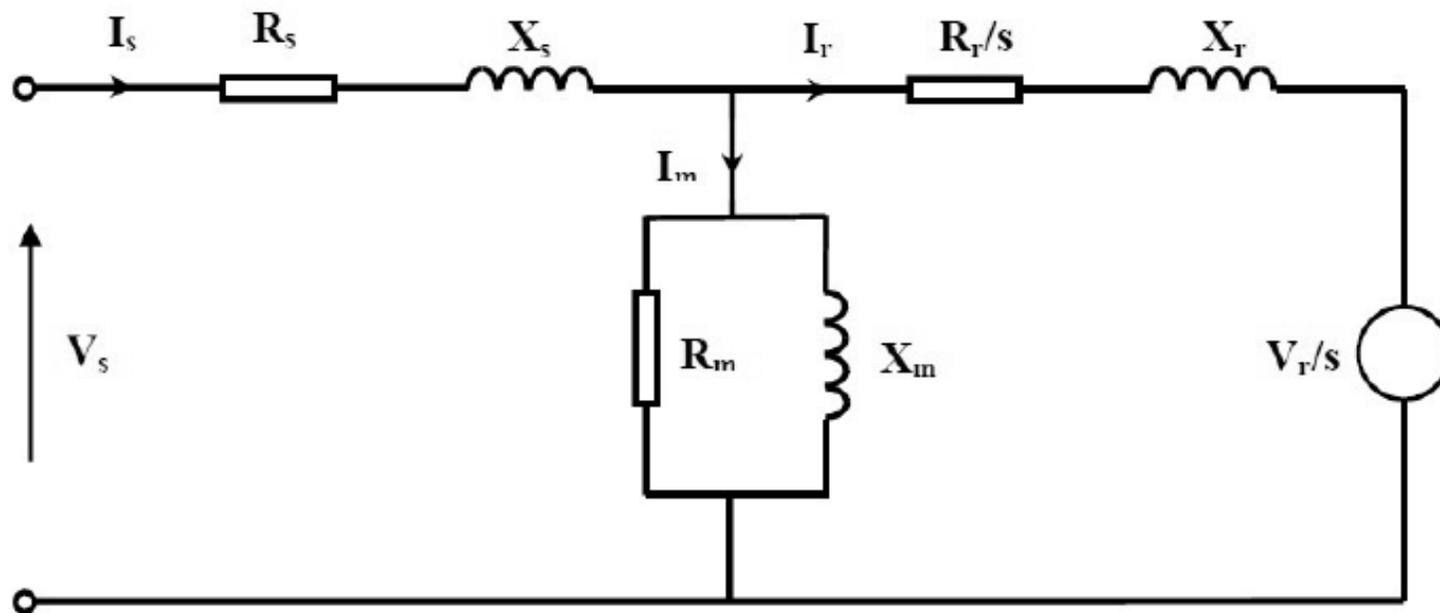
Type 3, Variable speed with partial power electronics

- Doubly Fed Induction Generator DFIG
- Rotor winding connected through slip rings
- Converter rating ~30%



Equivalent DFIG circuit

Doubly Fed Induction Generator



DFIG

If losses neglected:

$$P_{air\ gap} = P_s$$

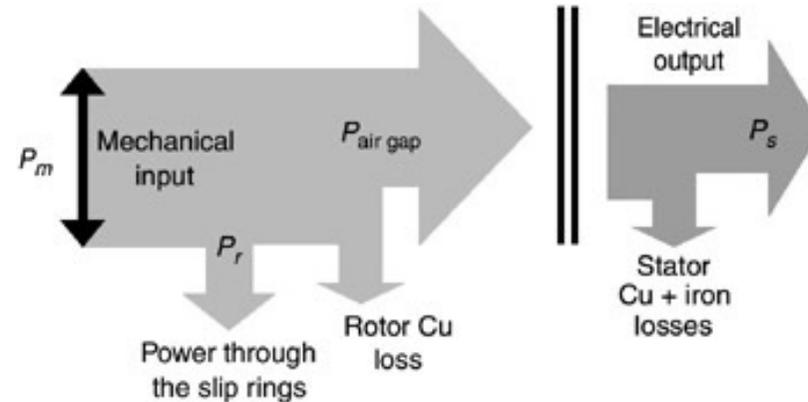
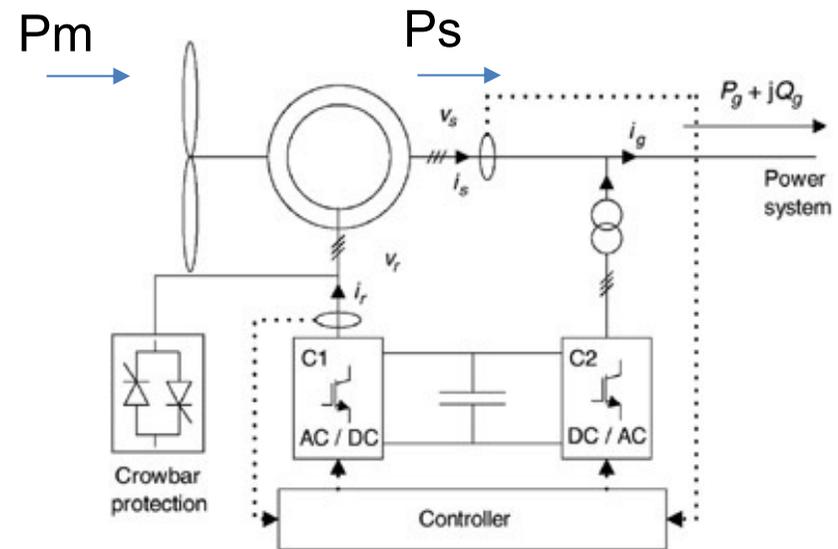
$$P_s = P_m - P_r$$

$$P_m = T\omega_r$$

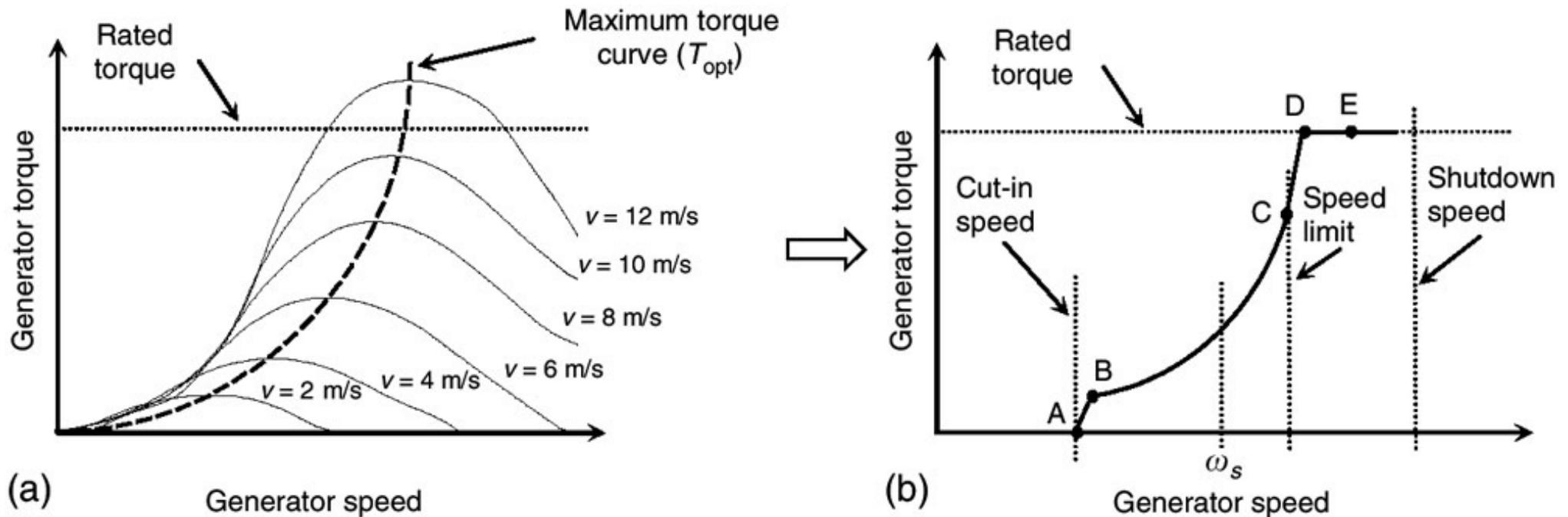
$$T\omega_s = T\omega_r - P_r$$

$$P_r = -T(\omega_s - \omega_r)$$

$$P_g = P_s + P_r$$

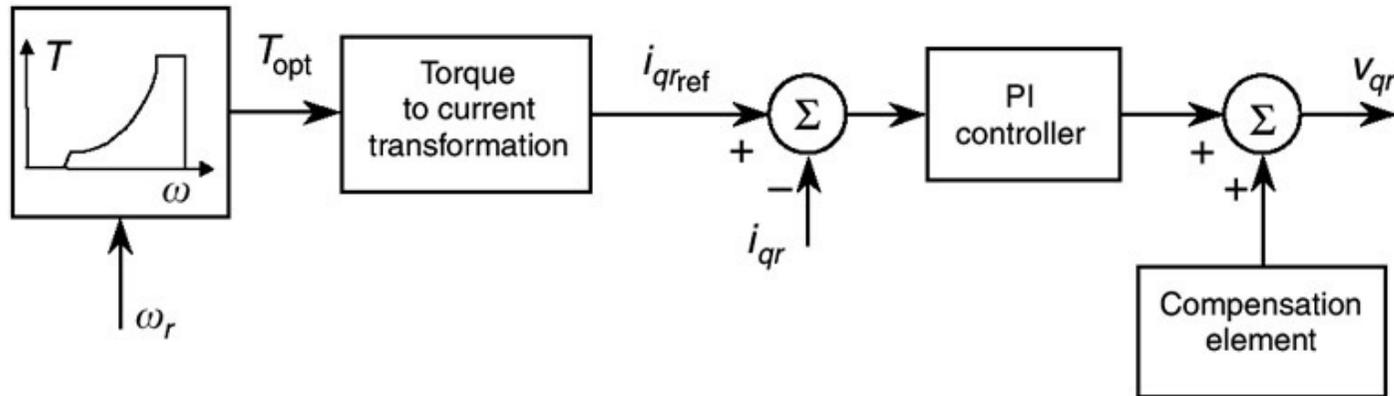


Wind turbine characteristic for maximum power extraction

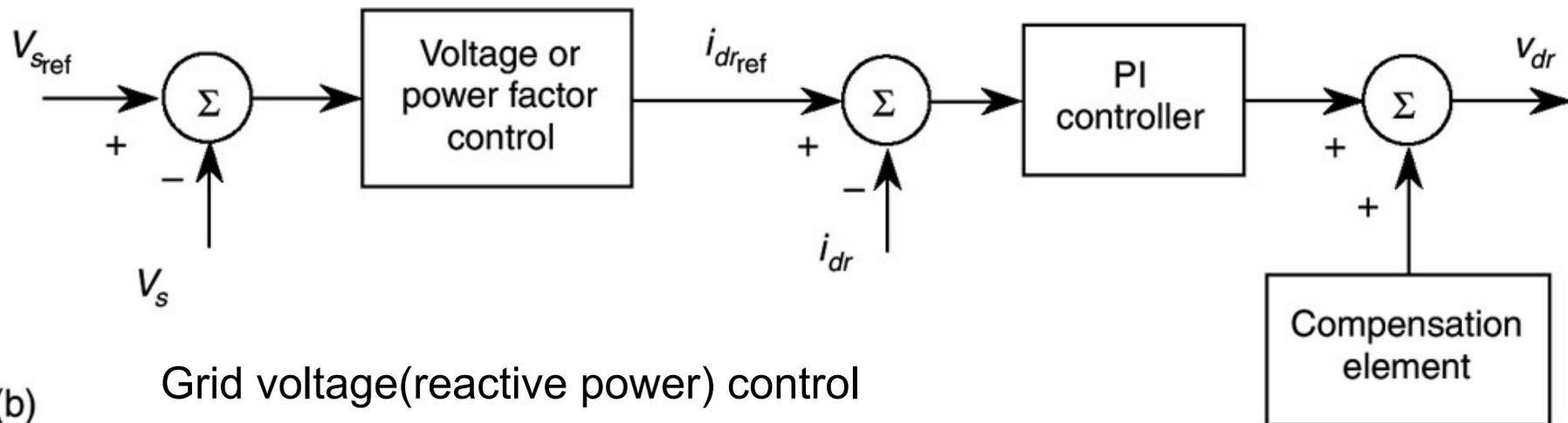


$$T_{opt} = K_{opt}\omega_r^2$$

DFIG rotor current control



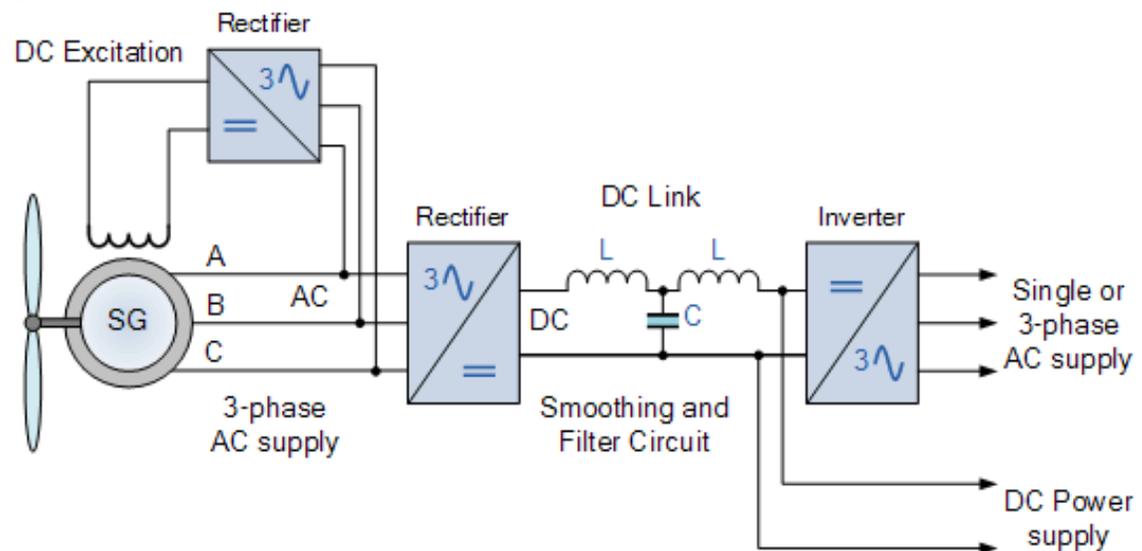
(a) Torque control



(b) Grid voltage(reactive power) control

Type 4, variable speed, full converter

- Synchronous generator
 - Wound or permanent magnet
 - With gear box or as Direct Drive
- Full size converter



Type 4 converter control

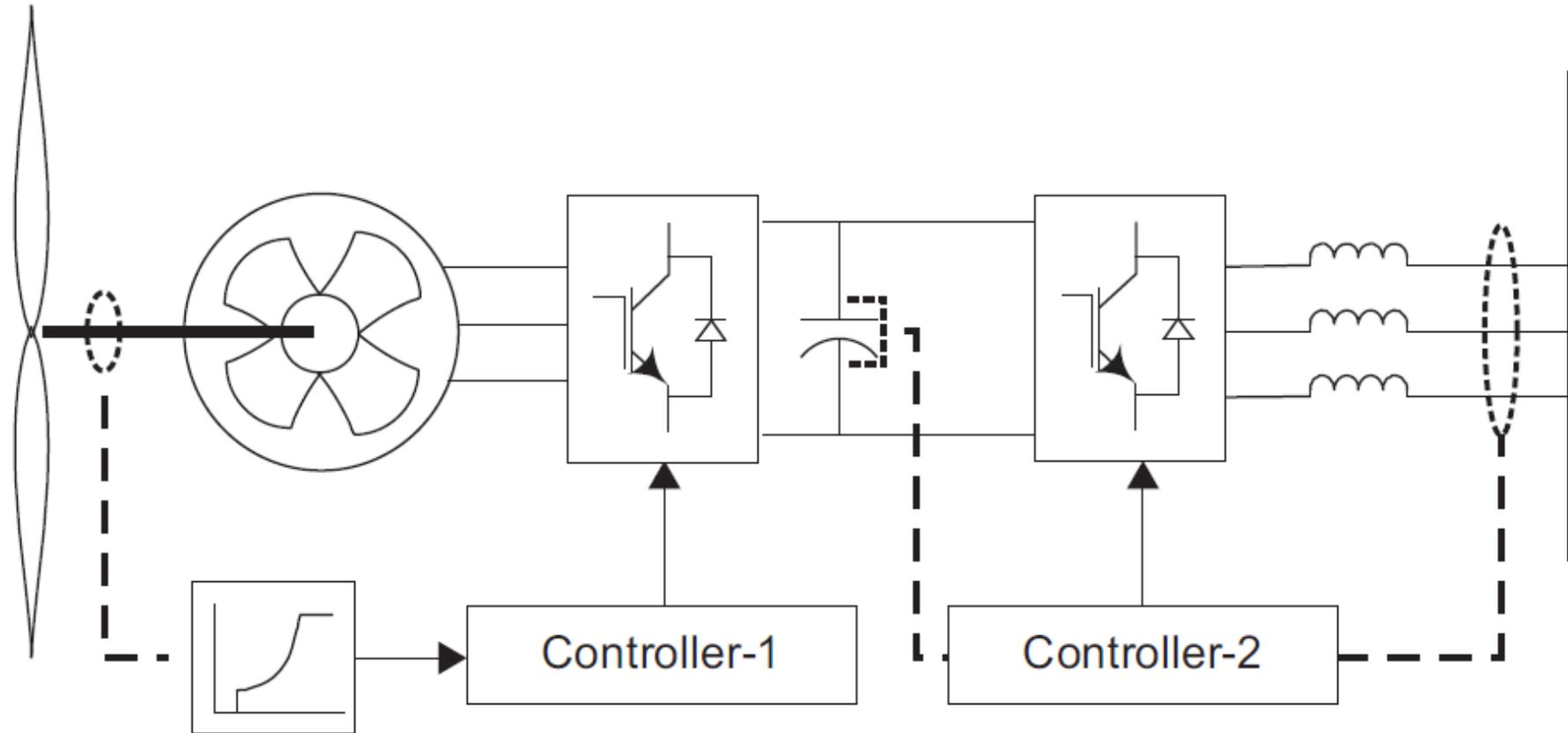
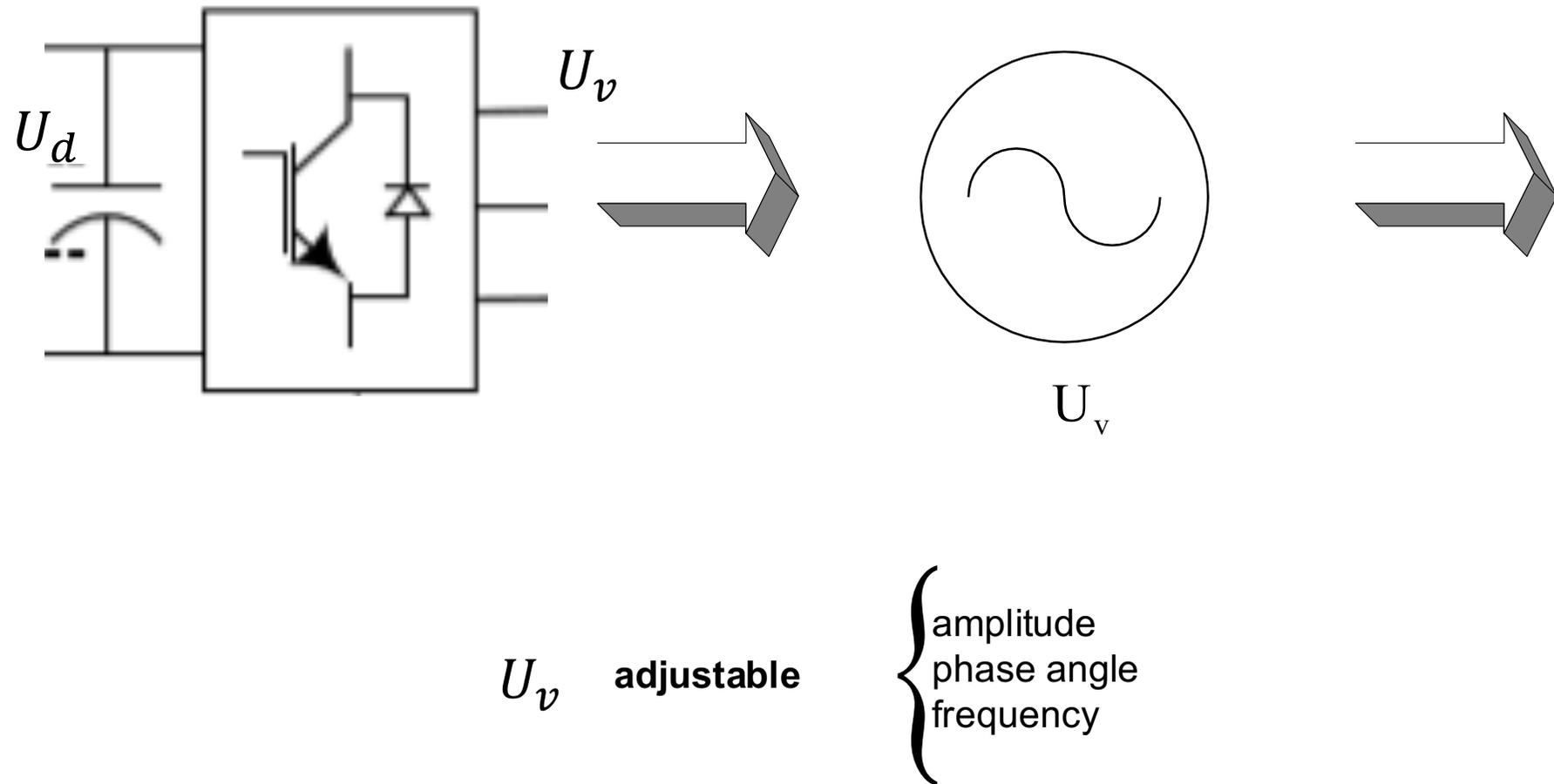
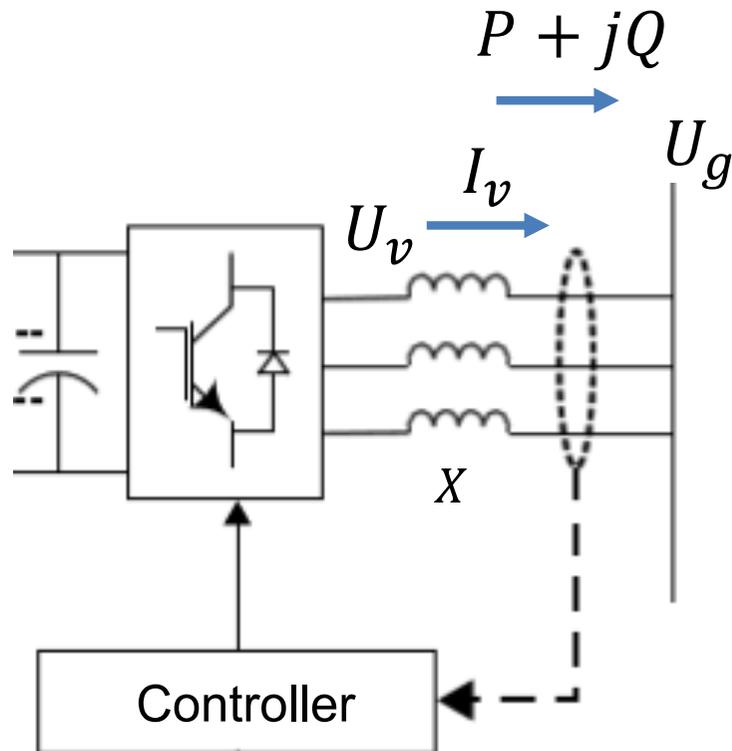


Figure 3.25 Wide-range synchronous generator wind turbine with a PWM-VSC generator-side converter

Basic control principle. Voltage Source Converter (VSC)



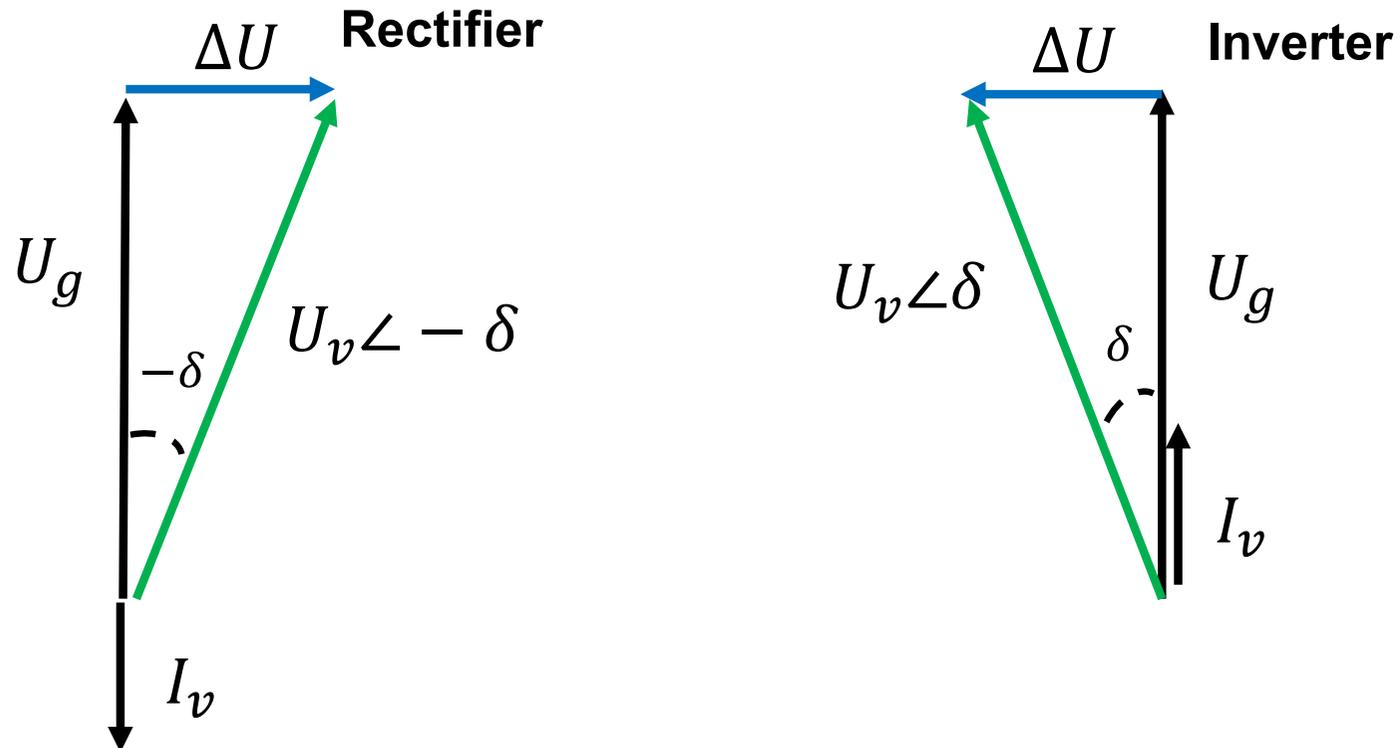
VSC power flow control



$$\bar{I}_v = \frac{U_v \angle \delta - U_g}{jX\sqrt{3}}$$

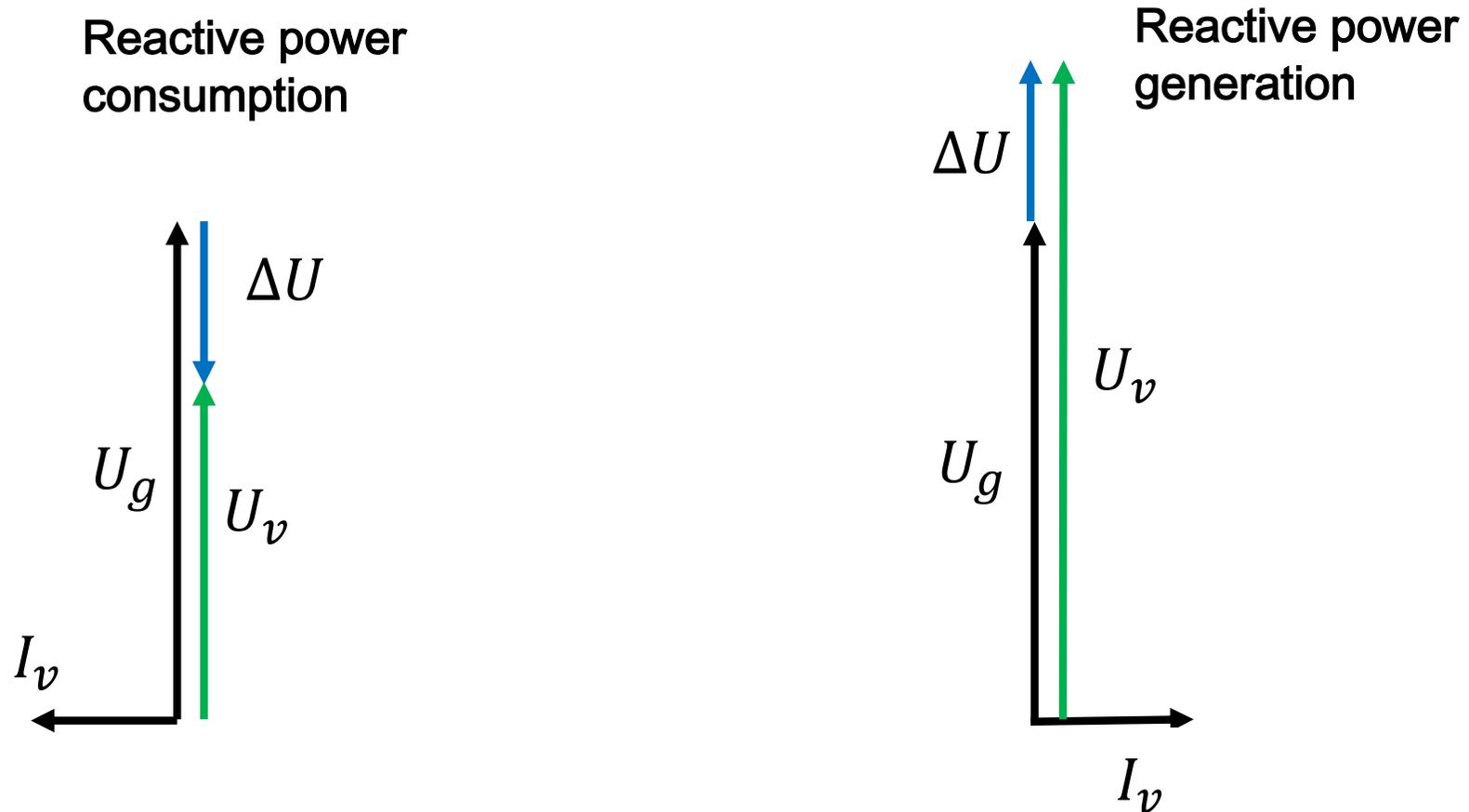
$$P + jQ = \sqrt{3} \cdot U_g \cdot \bar{I}_v^*$$

Control of Active Power



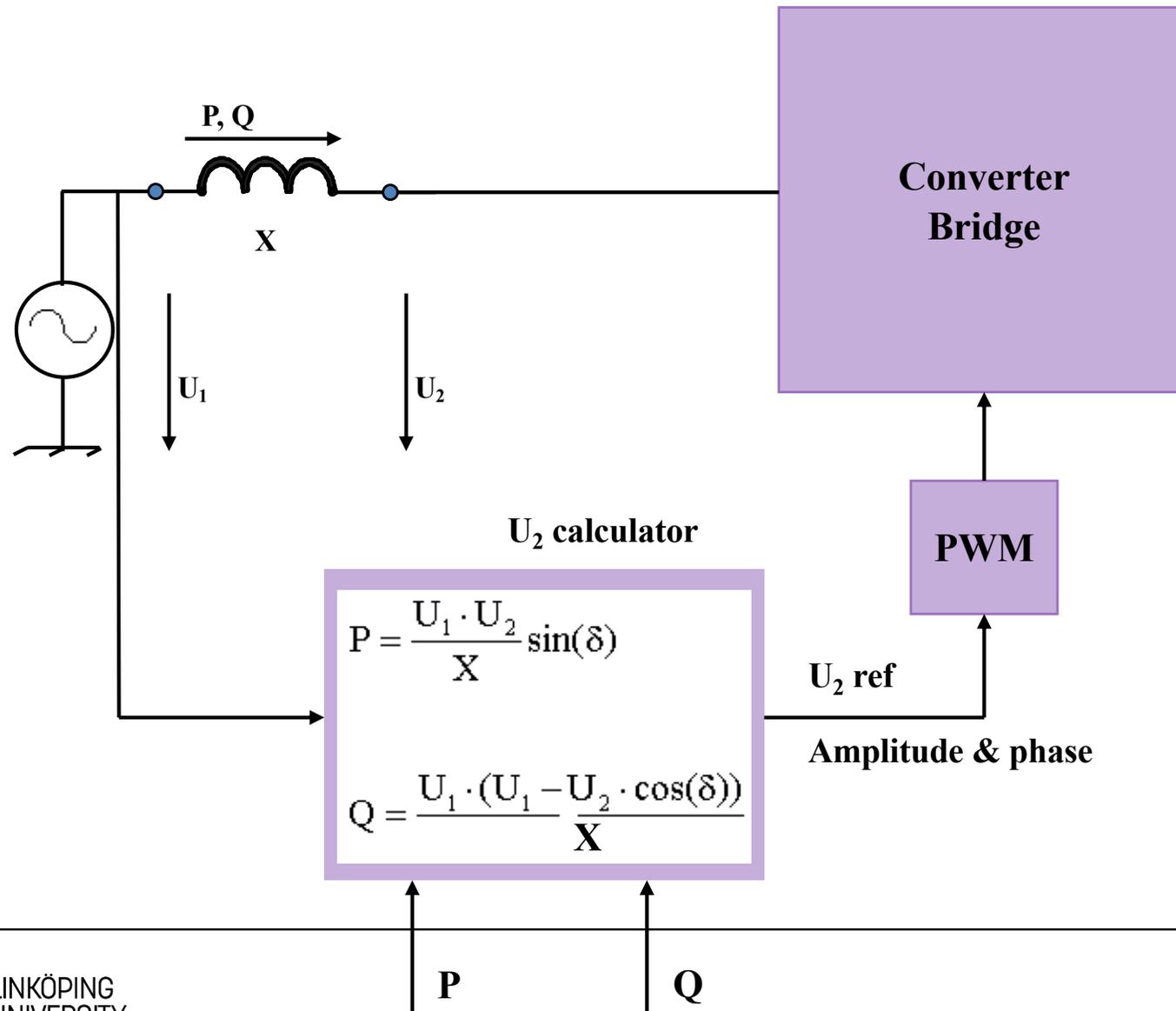
- If the U_v is in phase-lag, the active power flows from AC to DC side (**rectifier**)
- If the U_v is in phase-lead, the active power flows from DC to AC side (**inverter**)

Control of Reactive Power

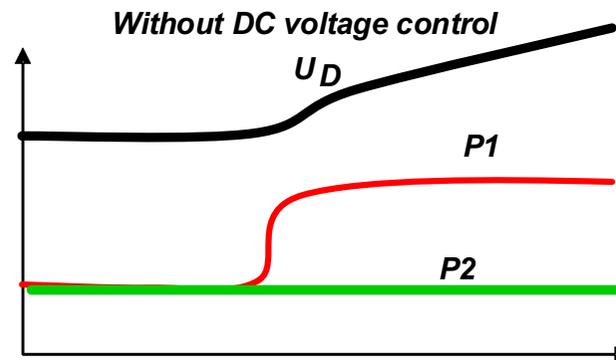
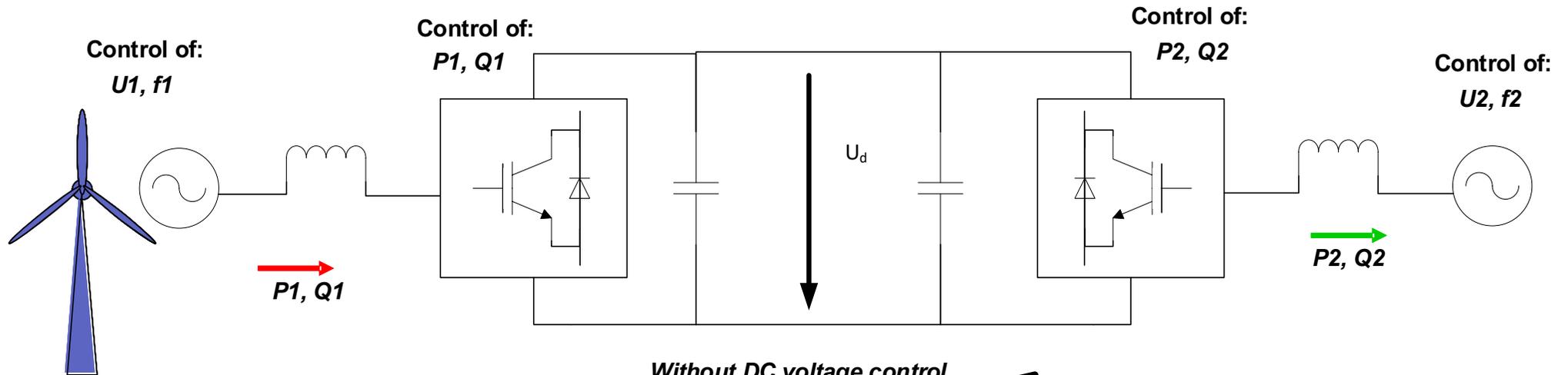


- If $U_v < U_g$ there is reactive power consumption.
- If $U_v > U_g$ there is reactive power generation.

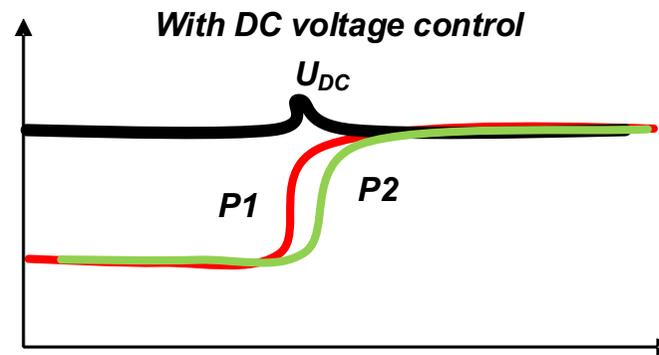
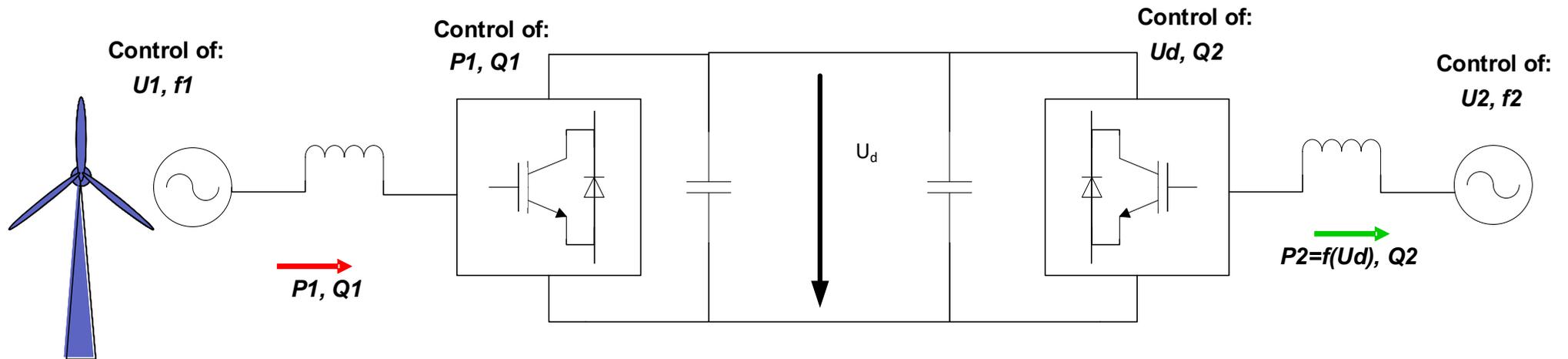
Calculation of Control Signal



DC Power versus DC voltage

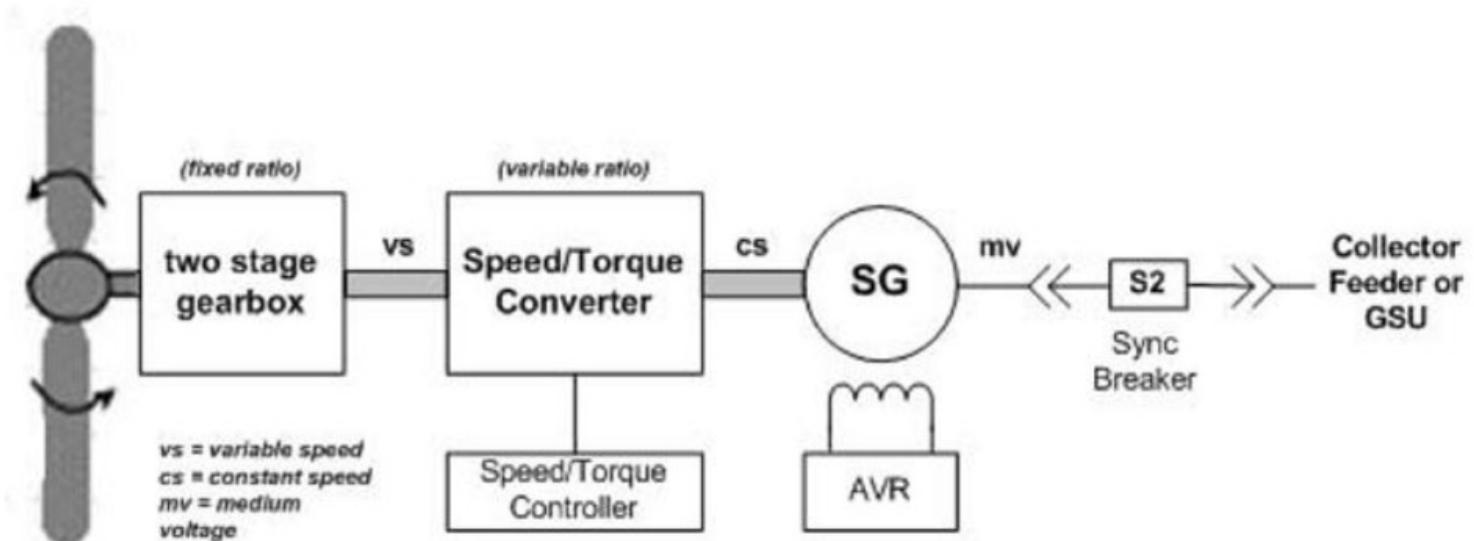


DC voltage control



Type 5, variable speed through torque/speed converter

- Hydraulic torque converter from low-speed shaft to high-speed shaft
- No converter for grid interface
- Synchronous generator



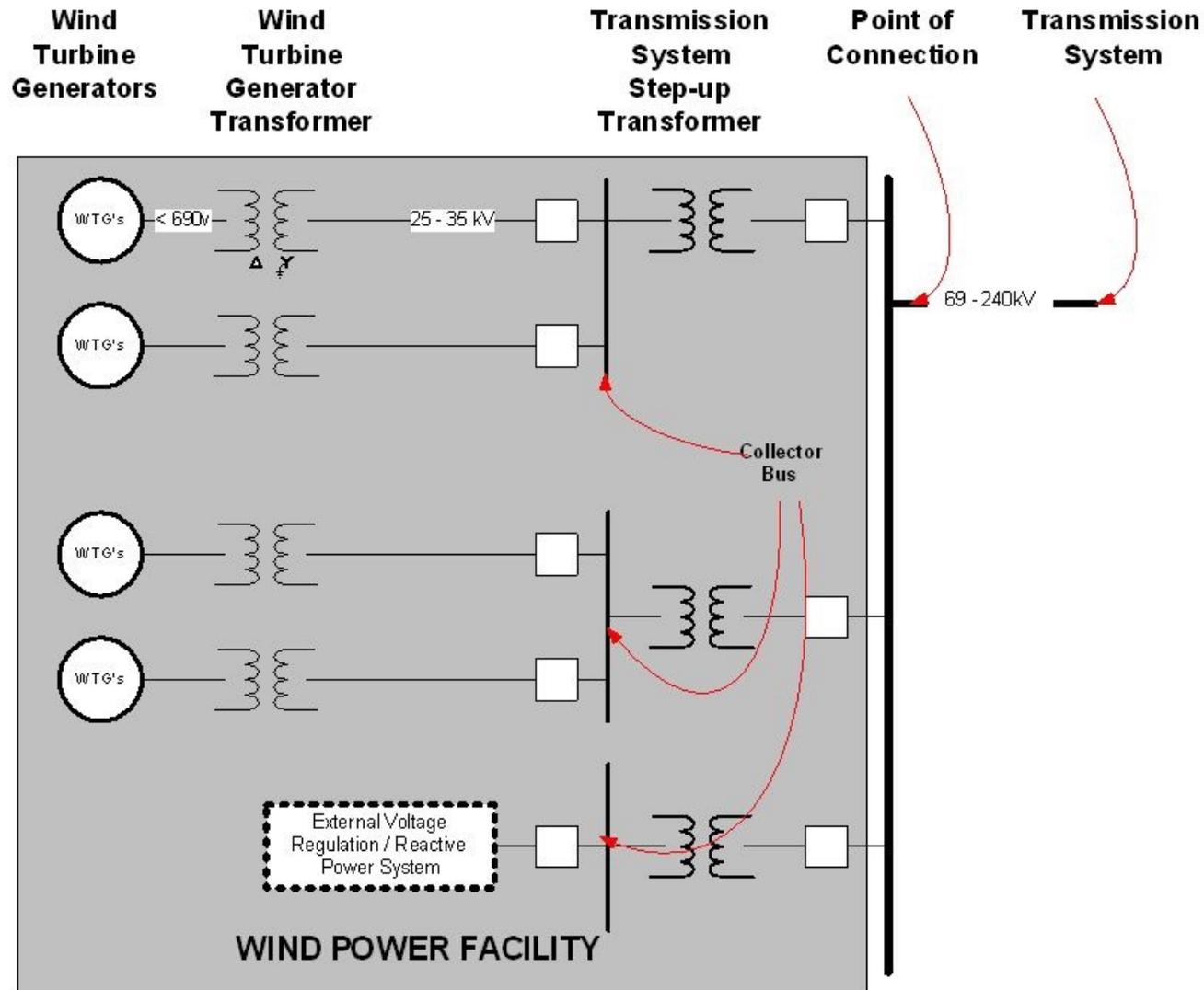
Comparison wind turbine types

	Type 1	Type 2, Optislip	Type 3, DFIG	Type 4, Full conv	Type 5, torque conv
Variable speed	No	Partial	Yes	Yes	Yes
Power limitation	Stall	Pitch control	Pitch control	Pitch control	Pitch control
Size	<1 MW	1 – 2 MW	< 4 MW	3 – 8 MW	
Torque control	No	Yes	Yes	Yes	Yes
Fault ride through	No	No	Yes	Yes	

Grid connection

Grid codes

Wind power grid connection



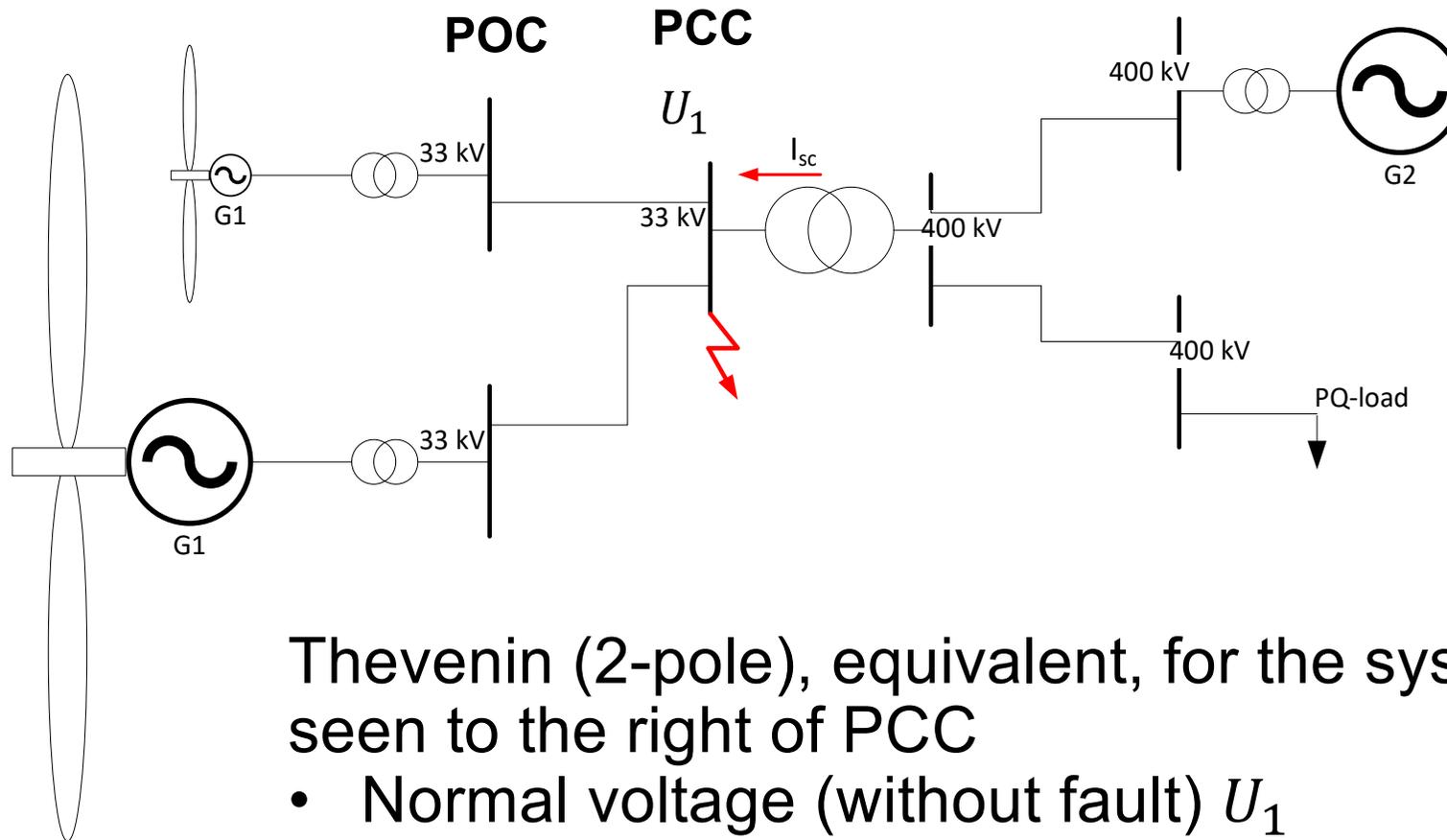
Point Of Connection, POC

The electrical connection point for equipment ownership

Point of Common Coupling, PCC

Electrical point where generation and consumers meet. Definition point for power quality requirements

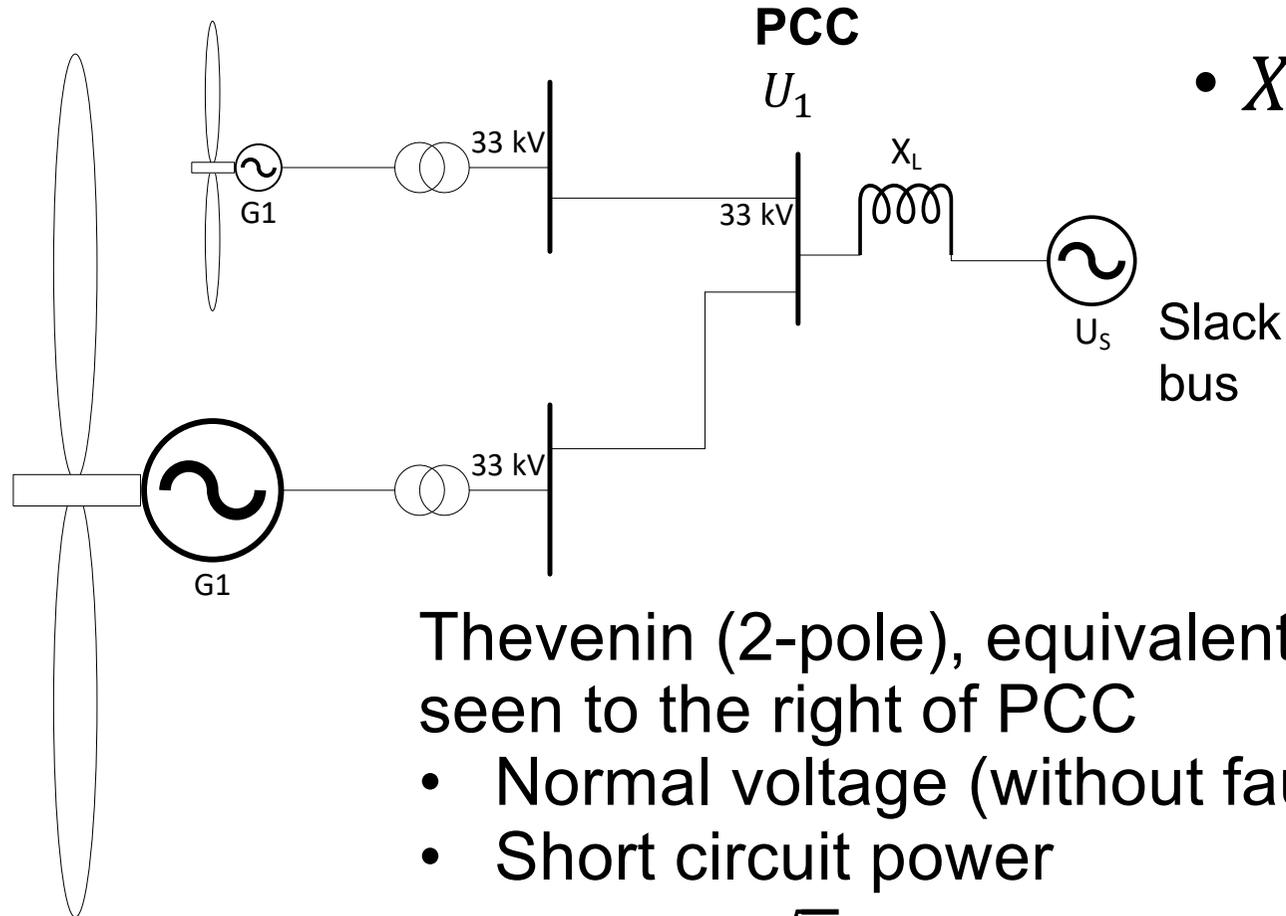
Grid connection of wind turbines



Thevenin (2-pole), equivalent, for the system seen to the right of PCC

- Normal voltage (without fault) U_1
- Short circuit current I_{sc}

Short Circuit Power



$$\bullet X_L = \frac{U_1^2}{S_{sc}}$$

Thevenin (2-pole), equivalent, for the system seen to the right of PCC

- Normal voltage (without fault) U_1
- Short circuit power

$$\bullet S_{sc} = \sqrt{3} \cdot U_1 \cdot I_{sc}$$

Electric power system roles

- Electric Utility
 - Commercial company for electricity production or electricity distribution (**DSO**)
 - Vattenfall, E.ON, EDF, National Grid
- Transmission System Operator (**TSO**)
 - Manage security and quality of power system. Ensure coordination between supply and demand.
 - Svenska Kraftnät (**SVK**)
 - European Network of Transmission System Operators for Electricity (**ENTSO-E**)

Grid connection requirements

Grid codes defined by TSO control

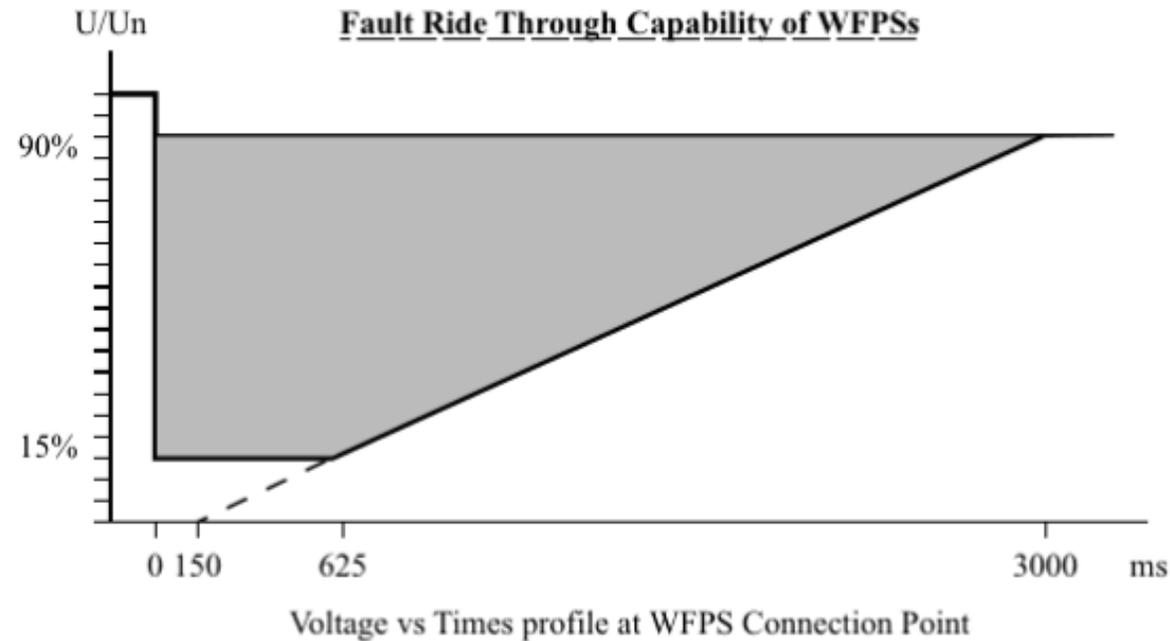
- Voltage stability
- Frequency stability
- Reactive power demand
- Fault handling
- Protection action
- Harmonics

Voltage and frequency requirements

Voltage Range (U/Un)	Time requirement, minimum
115–120%	2 seconds
110–115%	10 seconds
90–110%	Continuous operation
0–90%	As per Fault Ride Through Capability of WFPSs chart (CC.S2.3.6(a))

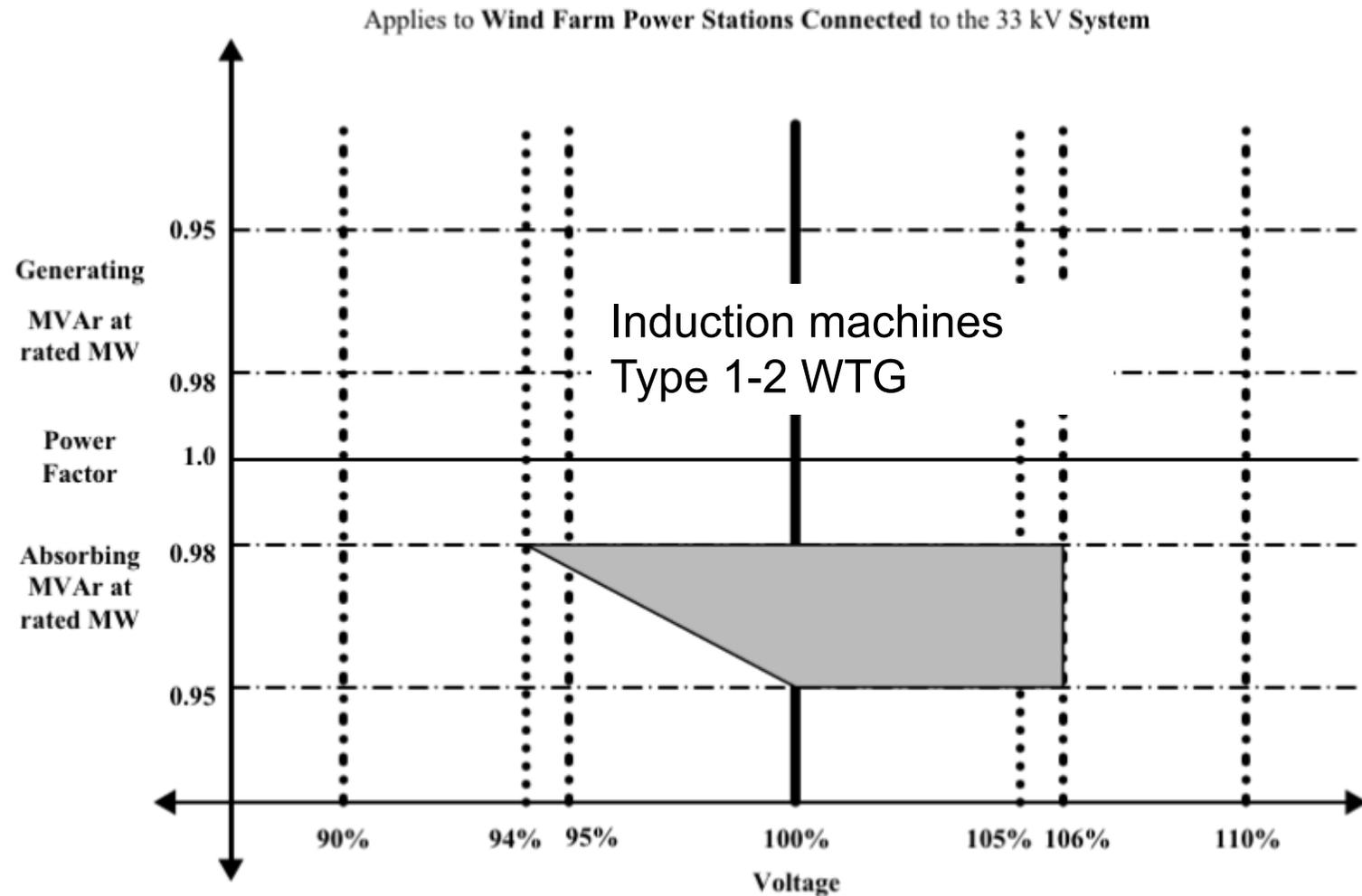
- WFPS, Wind Farm Power Station, Must remain in operation at
 - frequency 48.5 Hz - 49.0 Hz, > 30 minutes
 - frequency 49.0 Hz - 51.0 Hz, continuously
 - frequencies 51 Hz - 51.5 Hz, > 30 minutes

Fault ride through capability

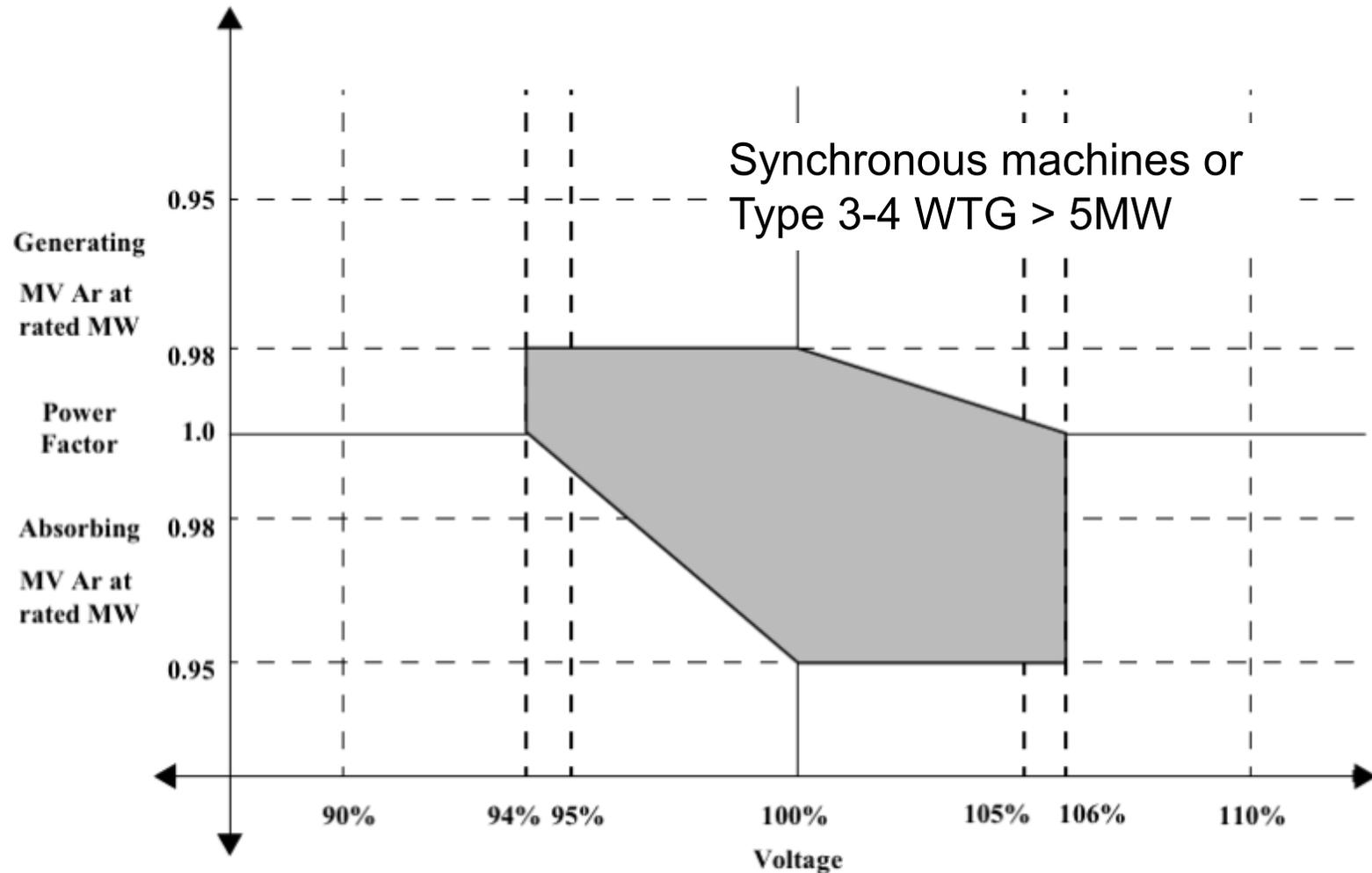


- Wind Farms shall remain connected for faults in the grey area.

Reactive power requirements for connection to 33 kV



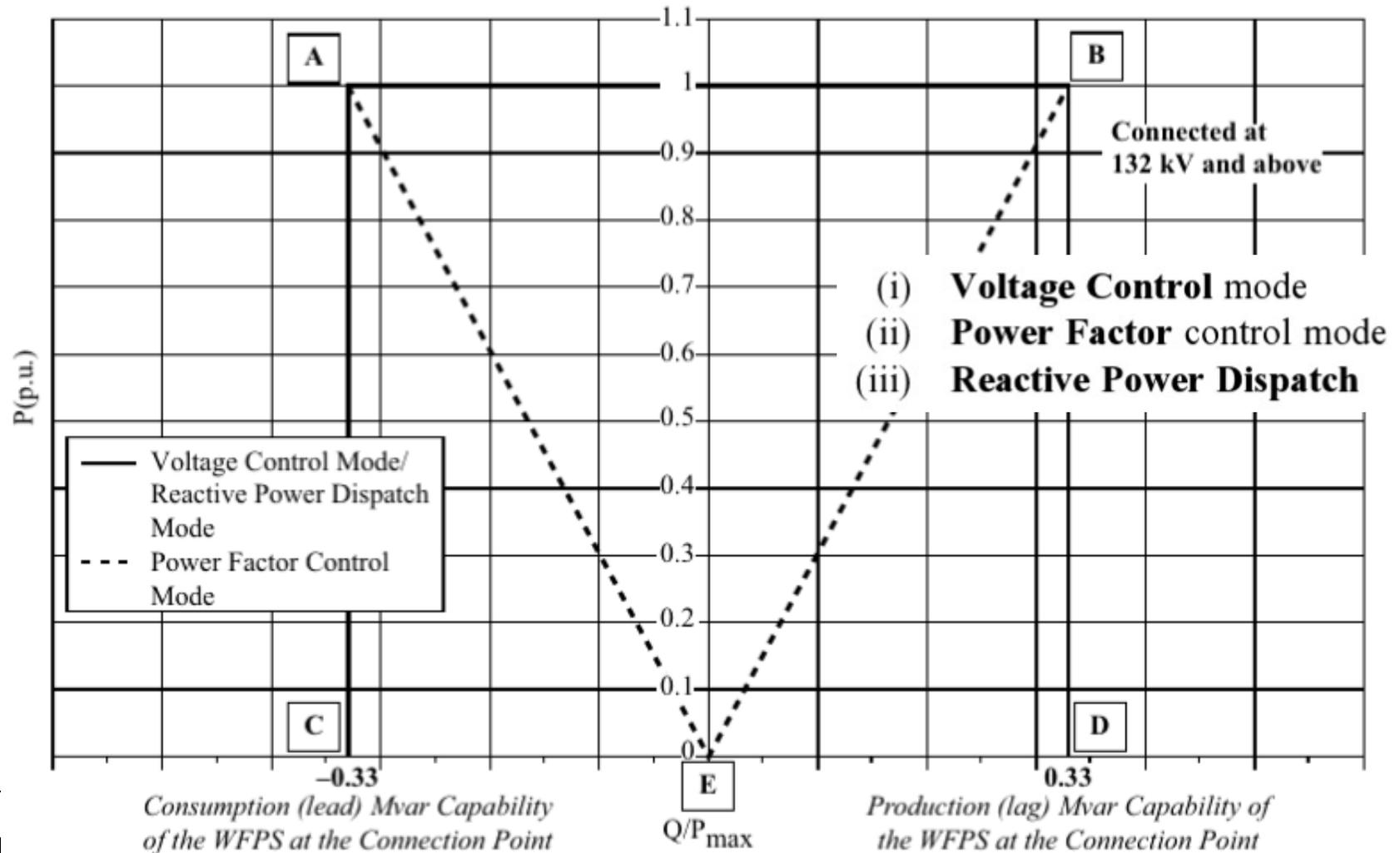
Reactive power requirements for connection to 33 kV



Type B Generating Units

Reactive power requirements for connection to 132 kV and above

Minimum Reactive Capability Characteristic of WFPS at the Connection Point

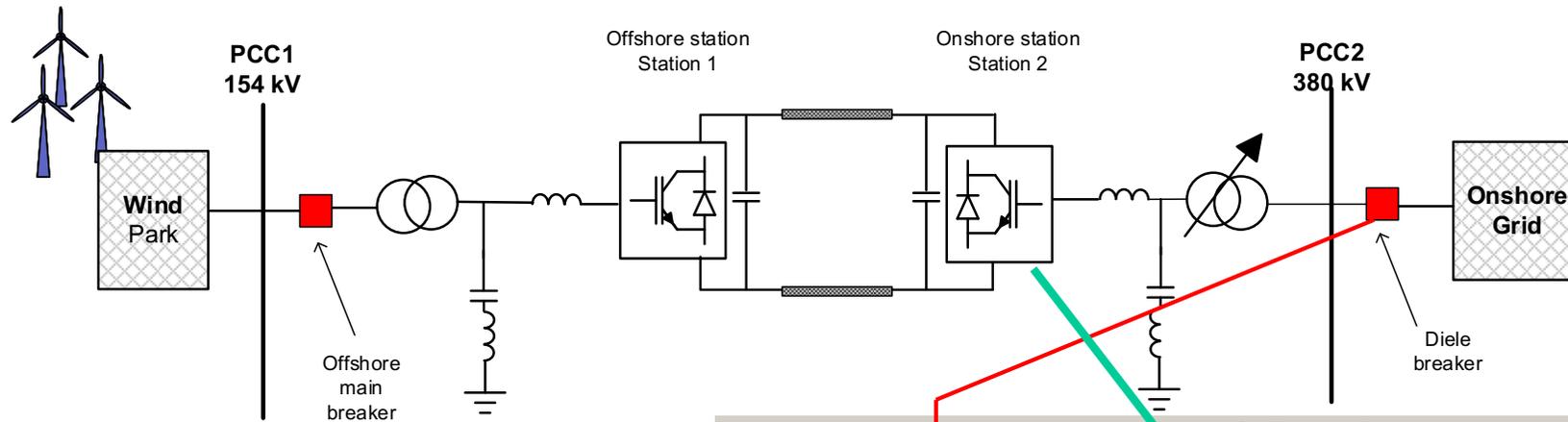


Power quality issues of wind turbines

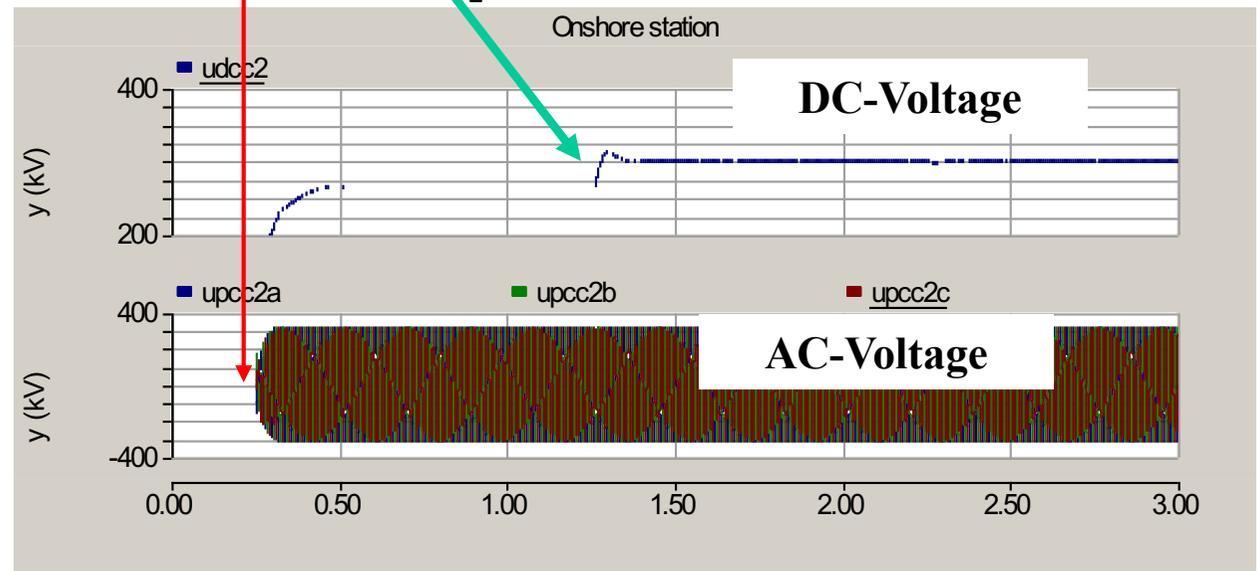
- Power fluctuations related to pulsation when the blade passes in front of the tower
- Pulsation frequency: $3 \times$ Rotor speed
- Converter harmonics

Offshore Windfarm Connection through HVDC

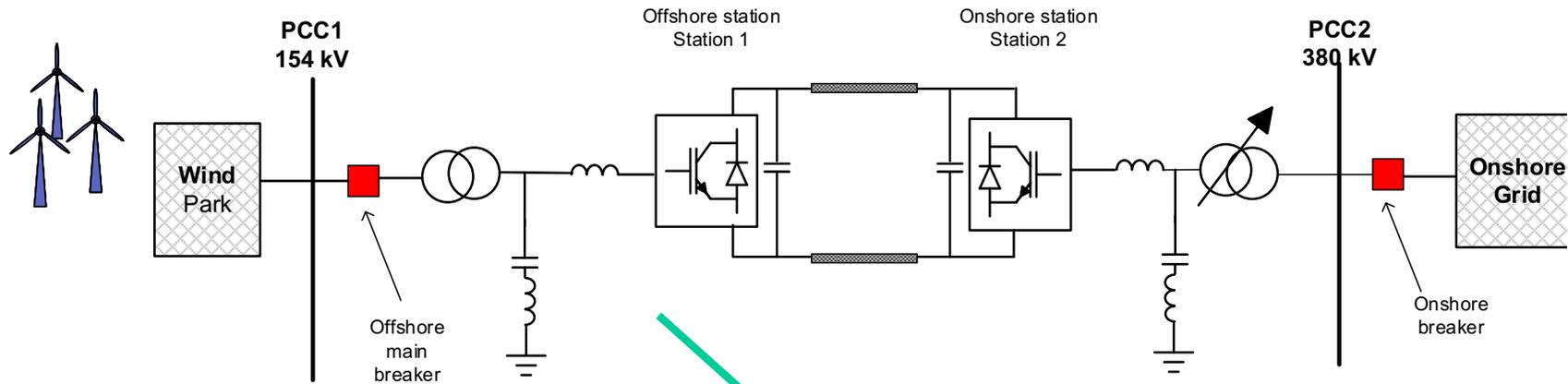
Converter energization



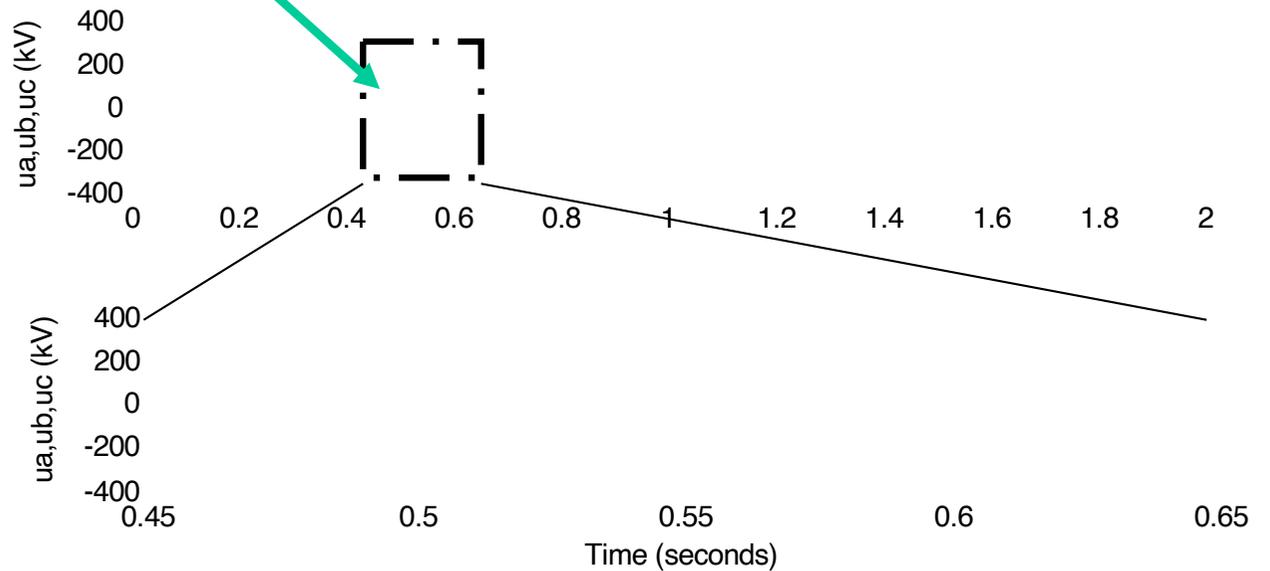
1. Auxiliary power connected. Cooling system running.
2. On-shore ac breaker closed to energize transformer, filter and converter
3. On-shore converter deblocked. DC-voltage control active



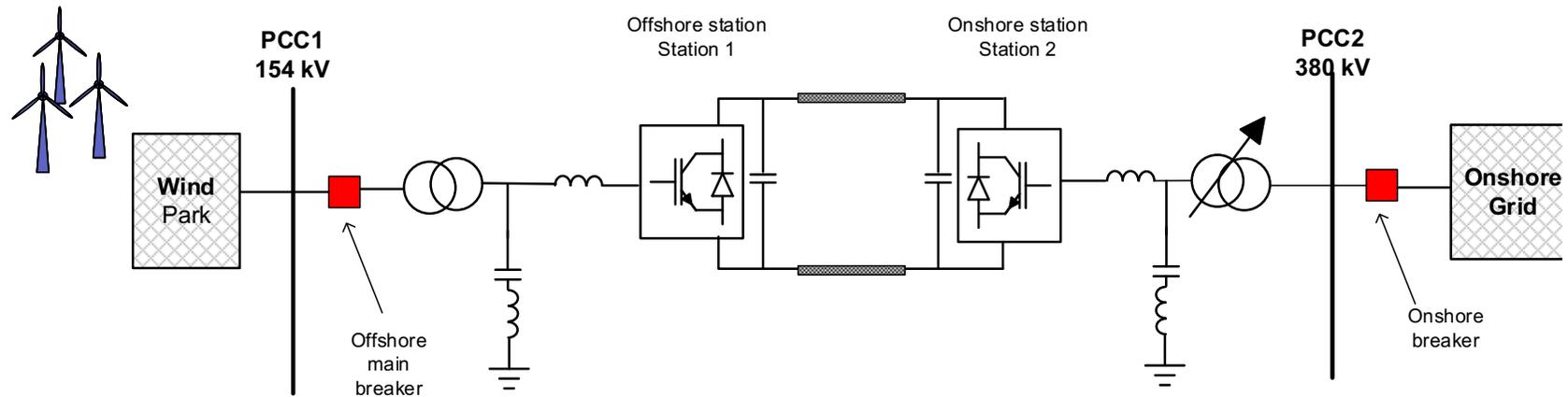
Off-shore grid energization



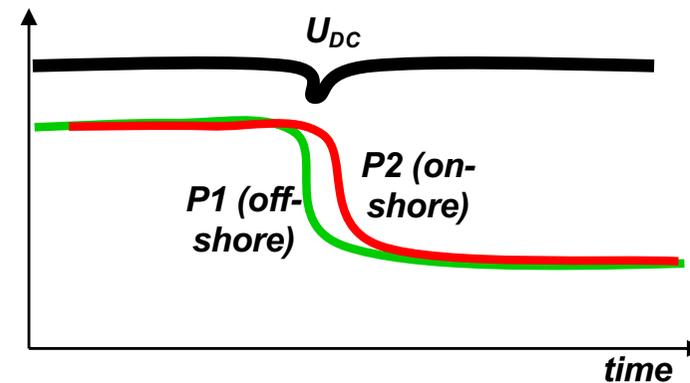
1. Off-shore converter deblocked. AC-voltage control active.
2. Smooth ramp-up of ac-voltage.
3. Off-shore main breaker closed.
4. Windpark transformers energized
5. Wind-turbines synchronized and connected



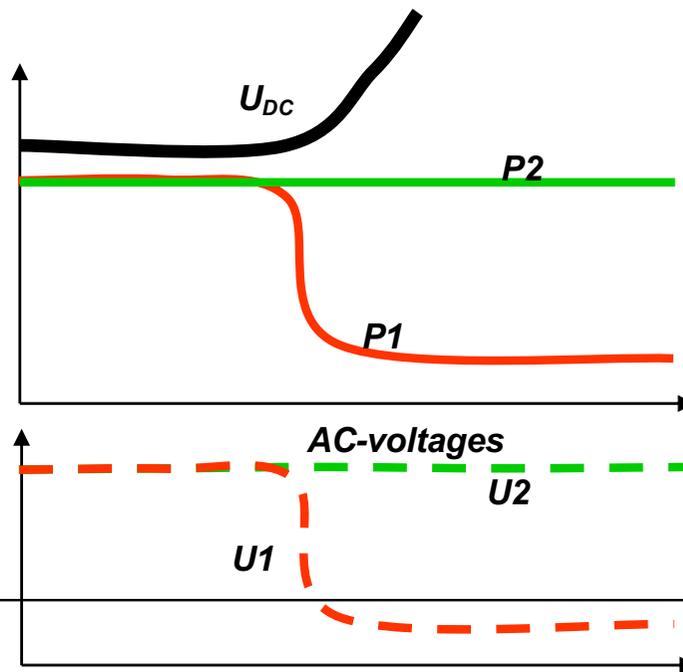
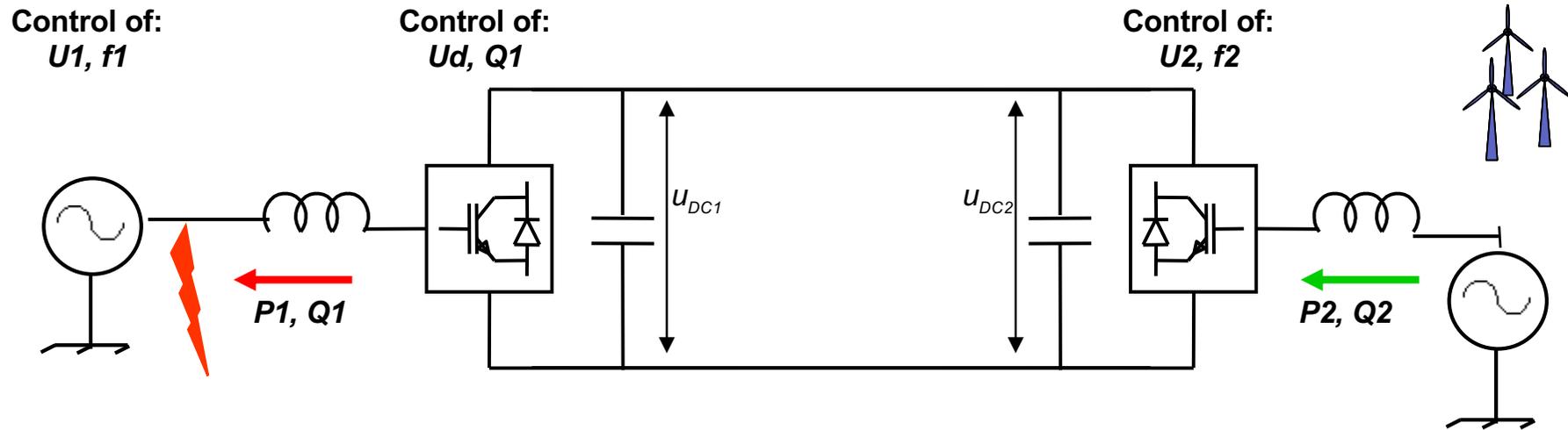
Normal operation



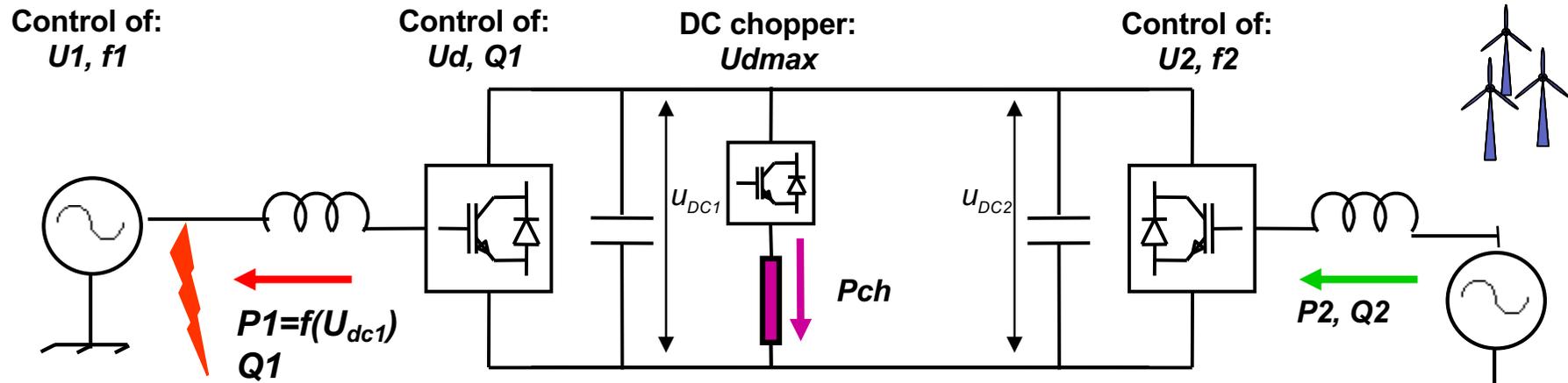
1. Off-shore converter in voltage and frequency control.
2. On-shore converter in dc-voltage and reactive power control.
3. **Windpark power reduction,**
4. Off-shore converter power (P_1) drops, since ac-voltage control results in power tracking
5. Instantaneous dc-power unbalance ($P_1 - P_2 < 0 \Rightarrow$ dc-voltage drop
6. On-shore dc-voltage control quickly reduces power (P_2) to restore nominal dc-voltage and power balance.



Isolated generation, grid fault without fault ride through

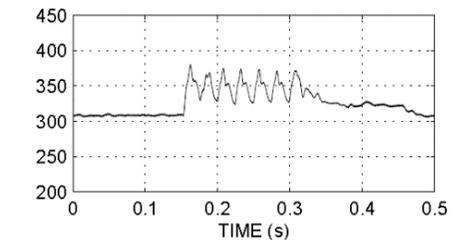
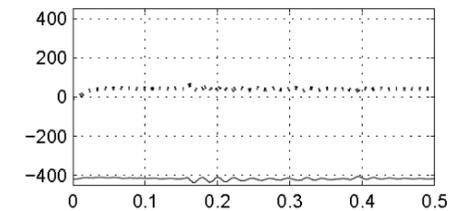
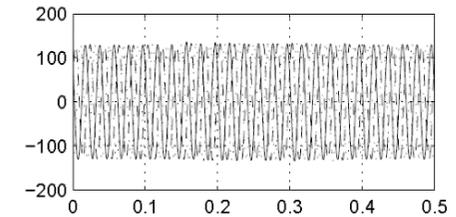
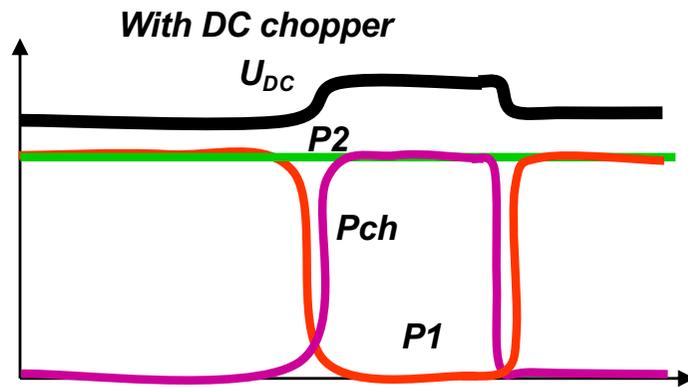
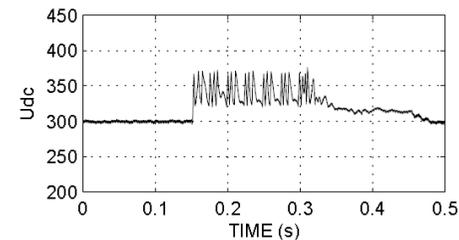
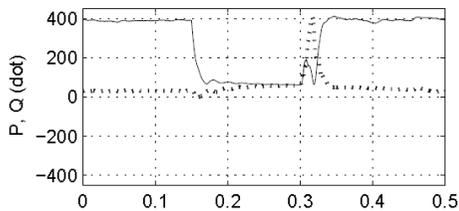
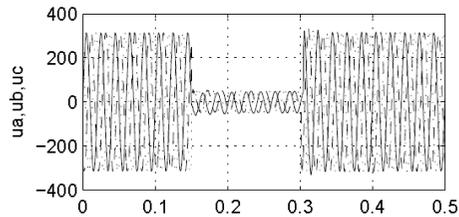


Fault ride through with chopper



On-shore

Off-shore



- DC-chopper decouples windpark from on-shore grid
- Minimum impact on wind production during on-shore grid faults

Chopper resistors

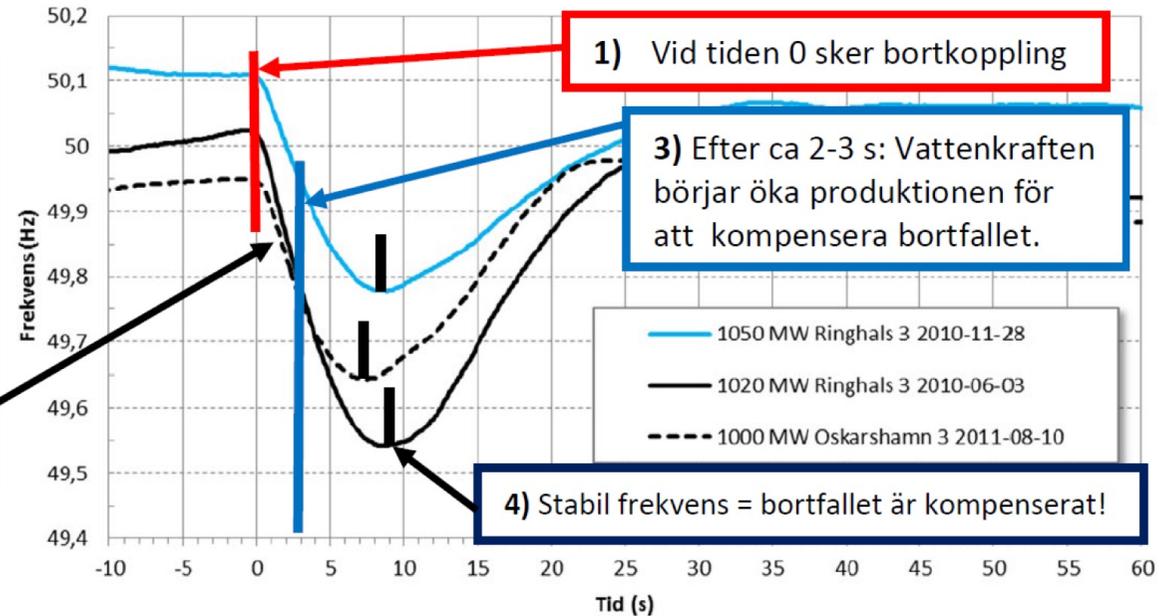


Stability

Frequency stability - Rotating mass

Rotating inertia in (primarily) directly connected synchronous machines contribute with inertia that stabilizes the grid.

2) Momentan kompensation kommer från energi från roterande komponenter. Då minskar deras rotations-hastighet och frekvensen i elnätet dalar



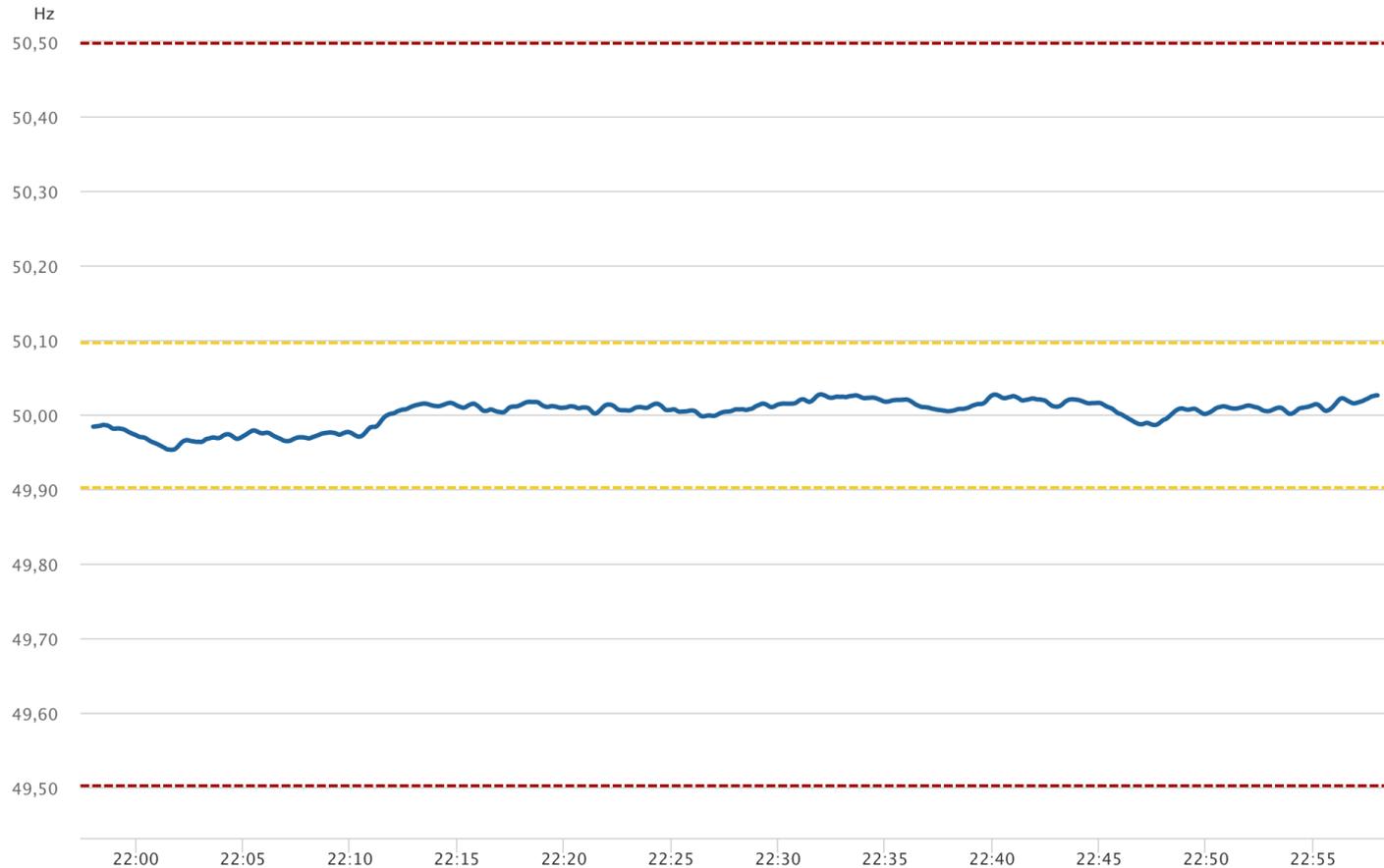
“Input power”+change in rotating energy=consumption

Wind power can contribute by adjusting turbine speed when grid frequency deviate from reference value.

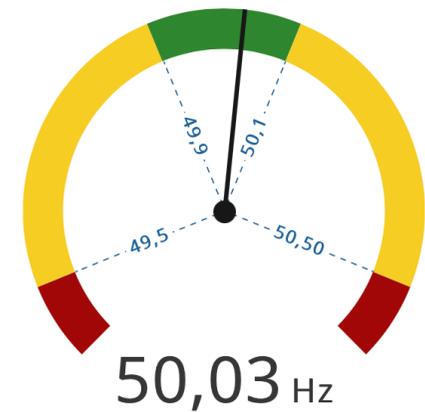


Frequency

Varies between 49.9Hz and 50.1Hz under normal operation in Sweden.



Frekvens klockan
22:58:00



SVK frequency reserve

Översiktlig kravbild för reserver

Uppdaterad 11 oktober 2023

Avhjälpande åtgärd	Frekvenshållningsreserver			Frekvensåterställningsreserver	
FFR	FCR-D upp	FCR-D ned	FCR-N	aFRR	mFRR
Snabb frekvensreserv (Fast Frequency Reserve)	Frekvenshållningsreserv -Störning uppreglering (Upward Frequency Containment Reserve - Disturbance)	Frekvenshållningsreserv -Störning nedreglering (Downward Frequency Containment Reserve - Disturbance)	Frekvenshållningsreserv -Normaldrift (Frequency Containment Reserve - Normal)	Automatisk Frekvens- återställningsreserv (Automatic Frequency Restoration Reserve)	Manuell Frekvens- återställningsreserv (Manual Frequency Restoration Reserve)
Uppreglering	Uppreglering	Nedreglering	Symmetrisk upp- och nedreglering	Upp- och/eller nedreglering	Upp- och/eller nedreglering
Minsta budstorlek 0,1 MW	Minsta budstorlek 0,1 MW	Minsta budstorlek 0,1 MW	Minsta budstorlek 0,1 MW	Minsta budstorlek 1 MW	Minsta budstorlek Kapacitetsmarknad: 1 MW** Energiaktiveringsmarknad: 5MW
Aktivering Automatiskt vid frekvensförändringar vid låg nivå av rotationsenergi	Aktivering Automatisk linjär aktivering inom frekvensintervallet 49,90-49,50 Hz	Aktivering Automatisk linjär aktivering inom frekvensintervallet 50,10-50,5 Hz	Aktivering Automatisk linjär aktivering inom frekvensintervallet 49,90-50,10 Hz	Aktivering Automatiskt vid frekvensavvikelse från 50,00 Hz	Aktivering Manuellt på begäran av Svenska kraftnät
Aktiveringstid Tre alternativ för 100 %: - 0,7 sek (vid 49,50 Hz) - 1,0 sek (vid 49,60 Hz) - 1,3 sek (vid 49,70 Hz)	Aktiveringstid Aktiveringstid för FCR-D upp redovisas i dokumentet med tekniska krav för frekvenshållningsreserver (FCR)	Aktiveringstid Aktiveringstid för FCR-D ned redovisas i dokumentet med tekniska krav för frekvenshållningsreserver (FCR)	Aktiveringstid Aktiveringstid för FCR-N redovisas i dokumentet med tekniska krav för frekvenshållningsreserver (FCR)	Aktiveringstid 100 % inom 5 minuter	Aktiveringstid 100 % inom 15 min
Volymkrav för Sverige Upp till ca 100 MW	Volymkrav för Sverige Upp till 558 MW	Volymkrav för Sverige Upp till 538 MW*	Volymkrav för Sverige 231 MW	Volymkrav för Sverige Upp till 111 MW	Volymkrav för Sverige Kapacitetsmarknad: Upp till 200 MW Energiaktiveringsmarknad: Inga volymkrav
Uthållighet - Uthållighet: 30 sek alternativt 5 sek - Repeterbarhet: Redo för aktivering inom 15 minuter	Uthållighet Uthållighet: Minst 20 min	Uthållighet Uthållighet: Minst 20 min	Uthållighet Uthållighet: 1 h	Uthållighet Uthållighet: 1 h	Uthållighet Uthållighet: 1 h

* Aktuell upphandlingsplan är lägre än volymkravet då FCR-D ned är en ny produkt sedan januari 2022. Upphandlingsplanen uppdateras kvartalsvis. Mer information finns på Svenska kraftnäts webbplats: www.svk.se/aktorsportalen/bidra-med-reserver/behov-av-reserver-nu-och-i-framtiden/

** Ett avropat bud på kapacitetsmarknaden innebär ett åtagande om att lämna bud på energiaktiveringsmarknaden.

För mer utförlig information om kraven, se Balansansvarsavtal och tillhörande regeldokument. De finns för nedladdning på Svenska kraftnäts webbplats: www.svk.se/aktorsportalen/balansansvarig/balansansvarsavtalet/

Trials for
wind
power to
operate on
these
markets.

TSTE26/Lars Eriksson

www.liu.se