Power Electronics – The Key Technology for Grid Integration of Renewables

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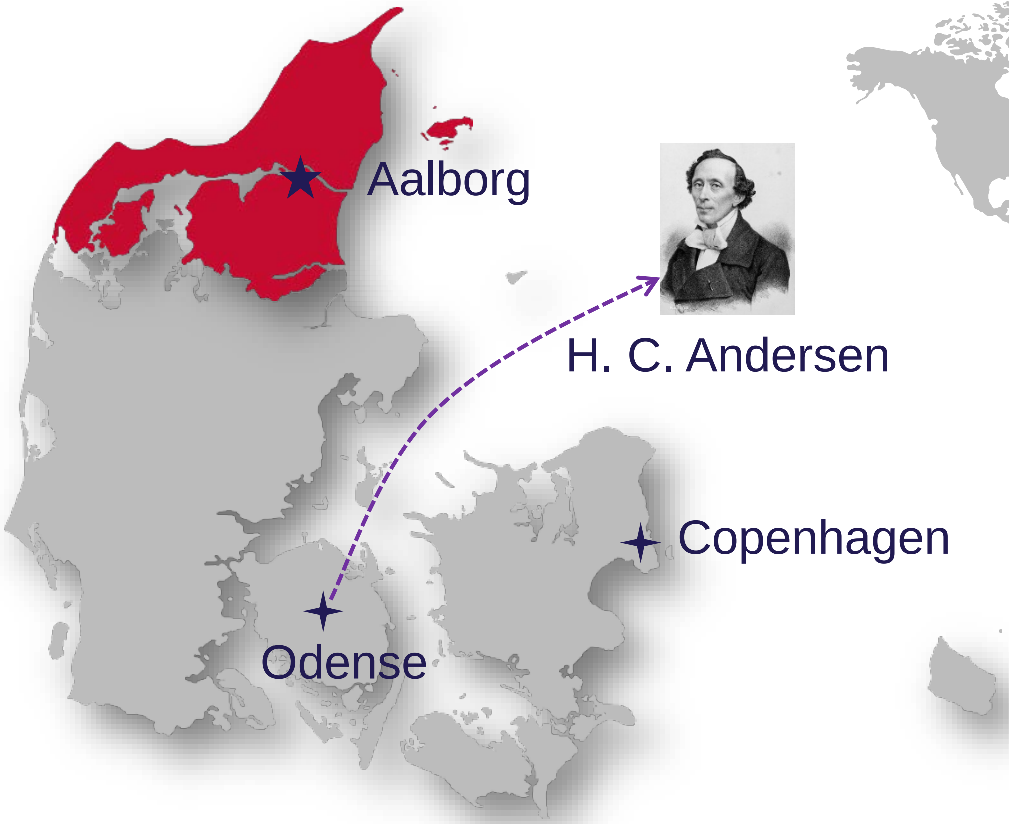
Outline

- **Overview of power electronics and renewable energy system**
  State-of-the-art; Technology overview, global impact
- **Demands for renewable energy systems**
  PV; Wind power; Mission Profiles, Grid Codes
- **Power converters for renewables**
  PV inverters at different power; Wind power application
- **Control for renewable systems**
  PV application; Wind power application
- **Summary**

▶ Aalborg University, Denmark



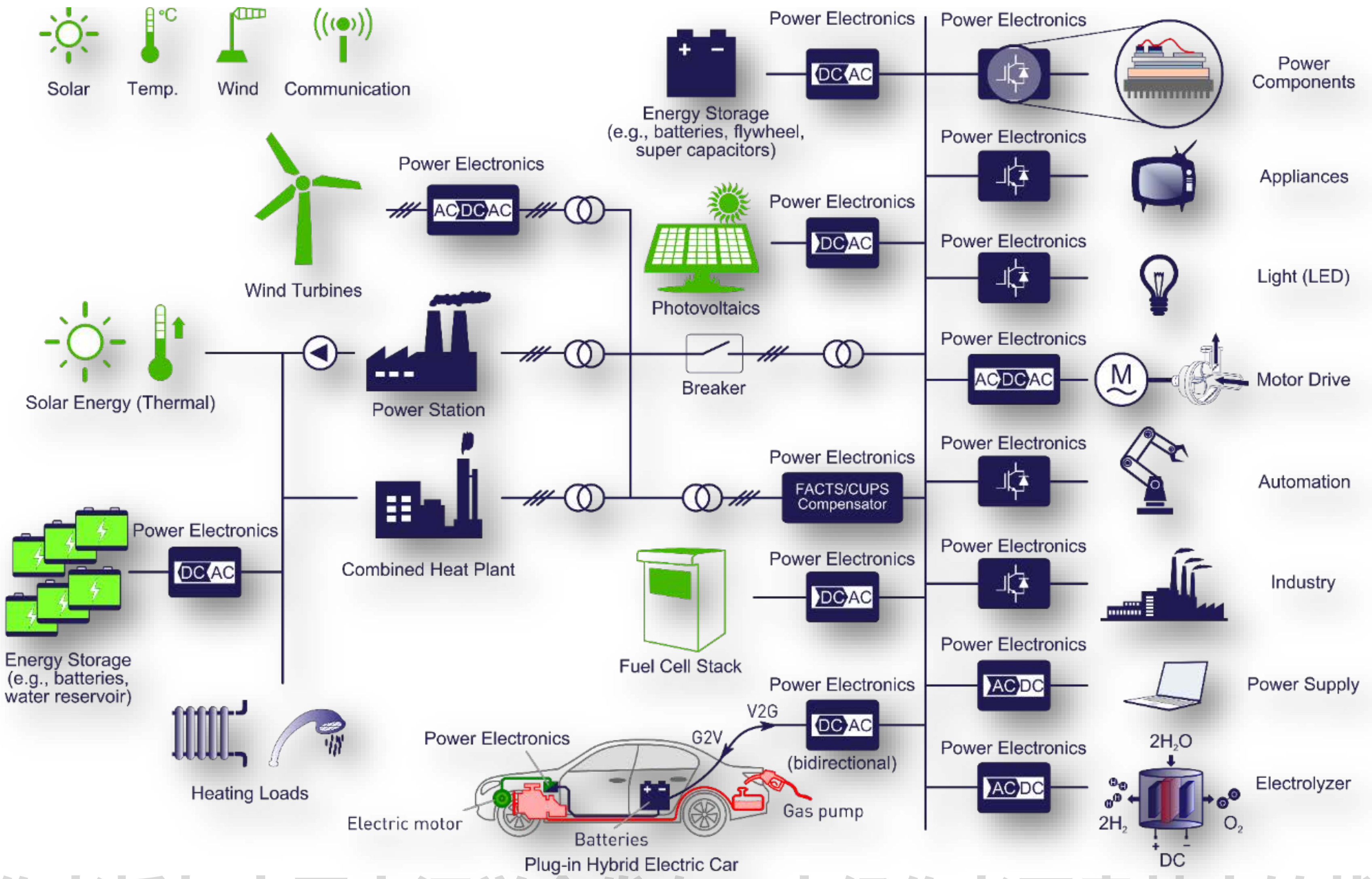
USNEWS 2019
Engineering
No. 4 globally
No. 1 in Europe
No. 1 in normalized citation impact globally
Source:
https://www.usnews.com/education/best-global-universities/engineering

Established in 1974
22,000 students
2,300 faculty

PBL-Aalborg Model
(Problem-based learning)

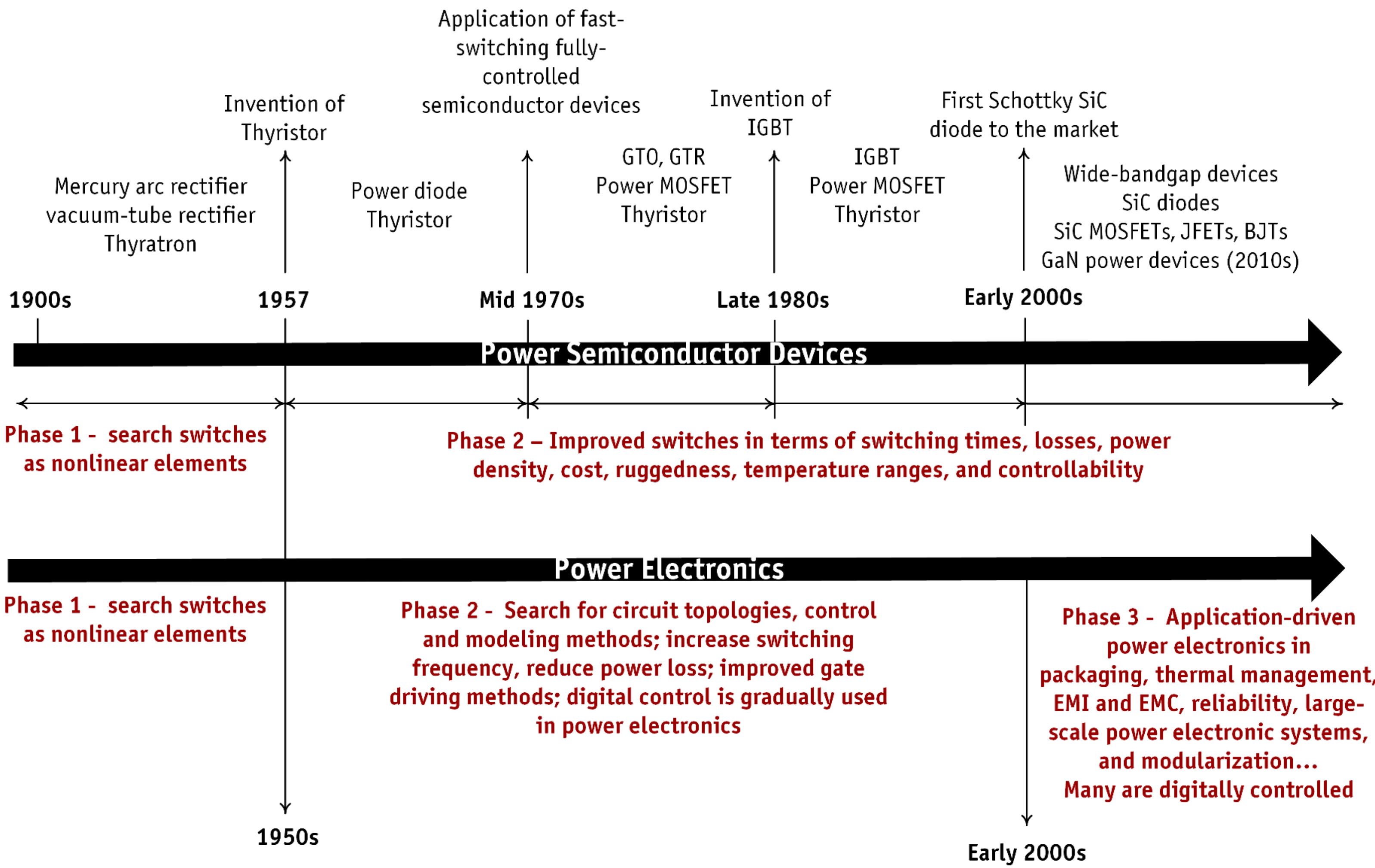
Overview of power electronics technology and renewable energy systems

Power Electronics in all aspects of Energy



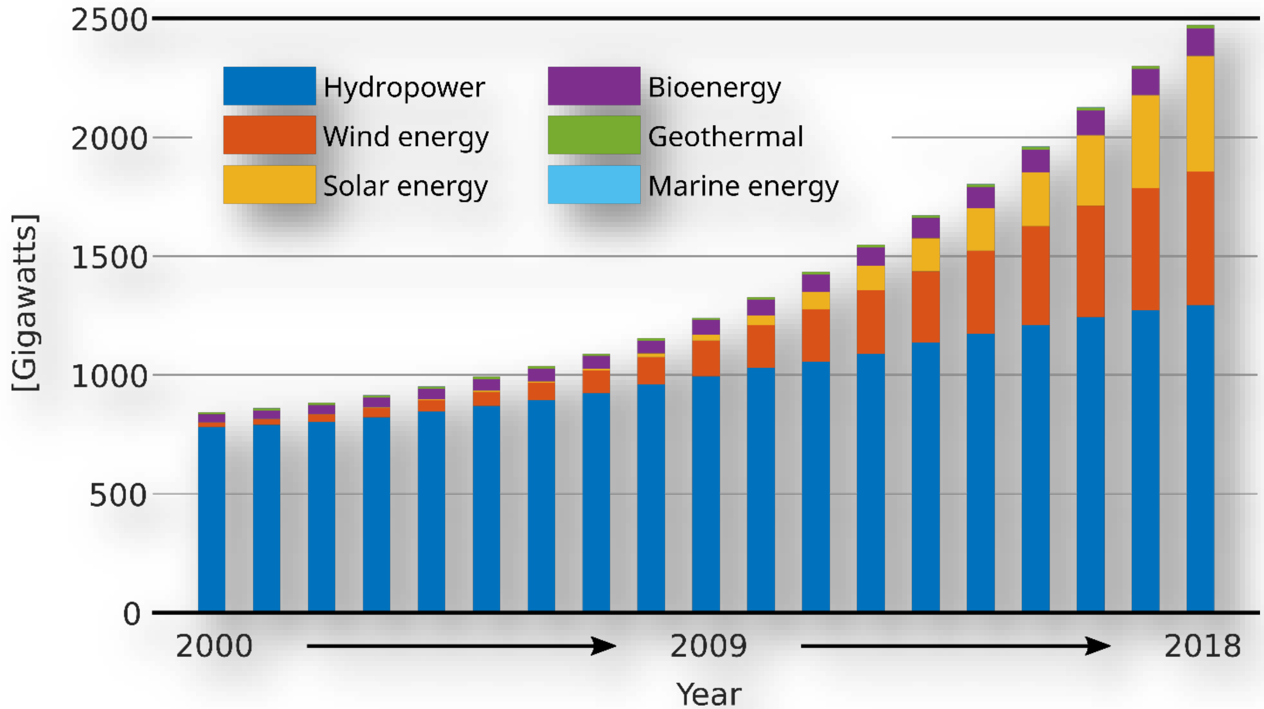
Energy Production | Distribution | Consumption | Control

100+ Years of Power Electronics



Reliability becomes one of the key application-oriented challenges

State of the Art – Renewable Evolution

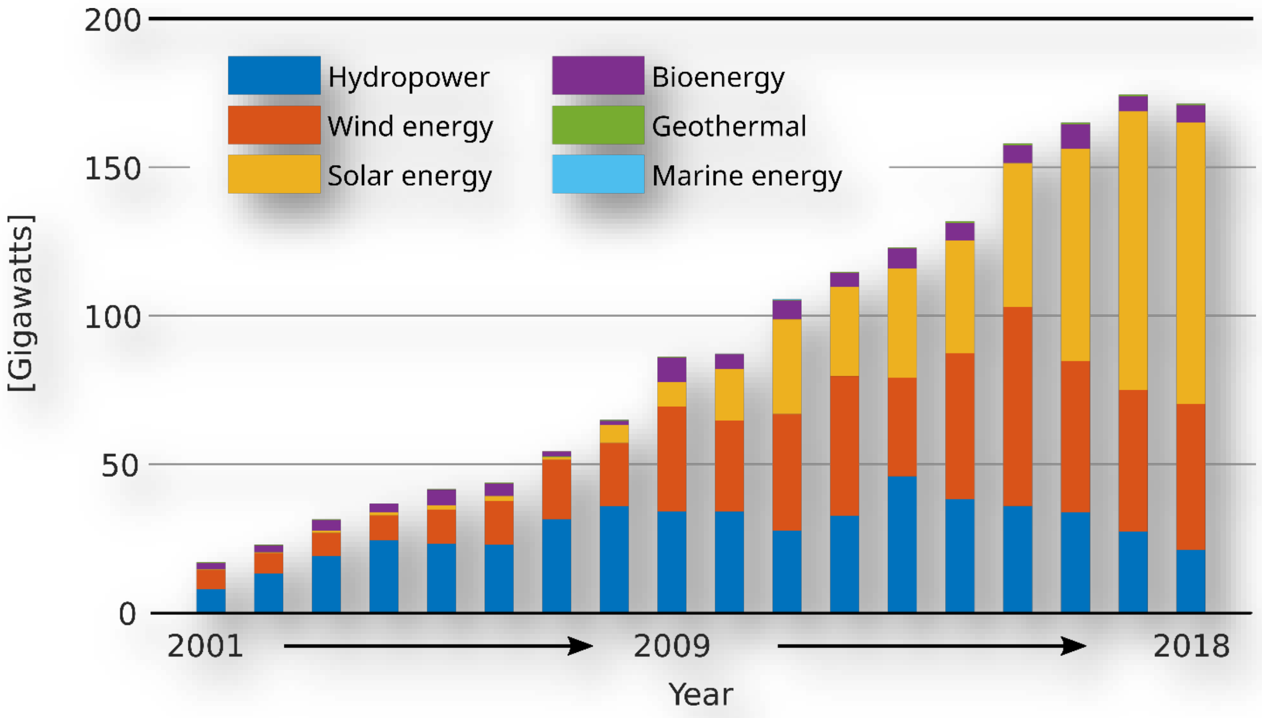


Worldwide Installed Renewable Energy Capacity (2000-2018)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy
3. Solar includes photovoltaics and solar thermal
4. Wind includes both onshore and offshore wind energy

(Source: IRENA, "Renewable energy capacity statistics 2019", http://www.irena.org/publications, March 2019)

Global RES Annual Changes

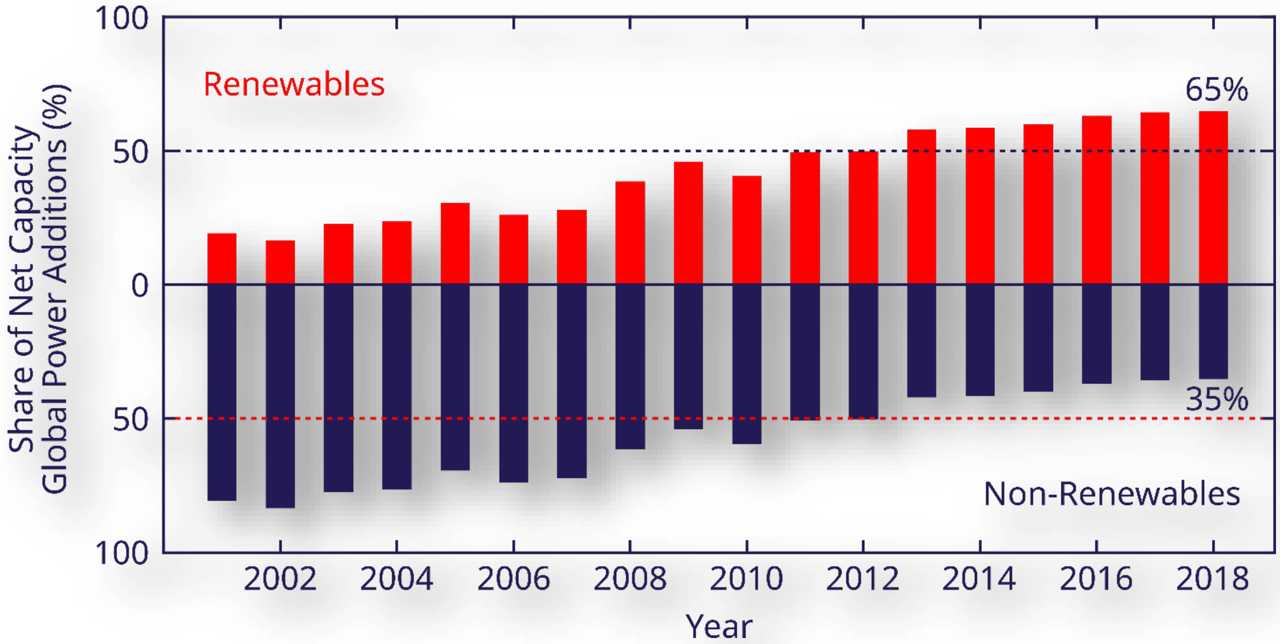


Global Renewable Energy Annual Changes in Gigawatt (2001-2018)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy
3. Solar includes photovoltaics and solar thermal
4. Wind includes both onshore and offshore wind energy

(Source: IRENA, "Renewable energy capacity statistics 2019", http://www.irena.org/publications, March 2019)

Share of the Net Total Annual Additions



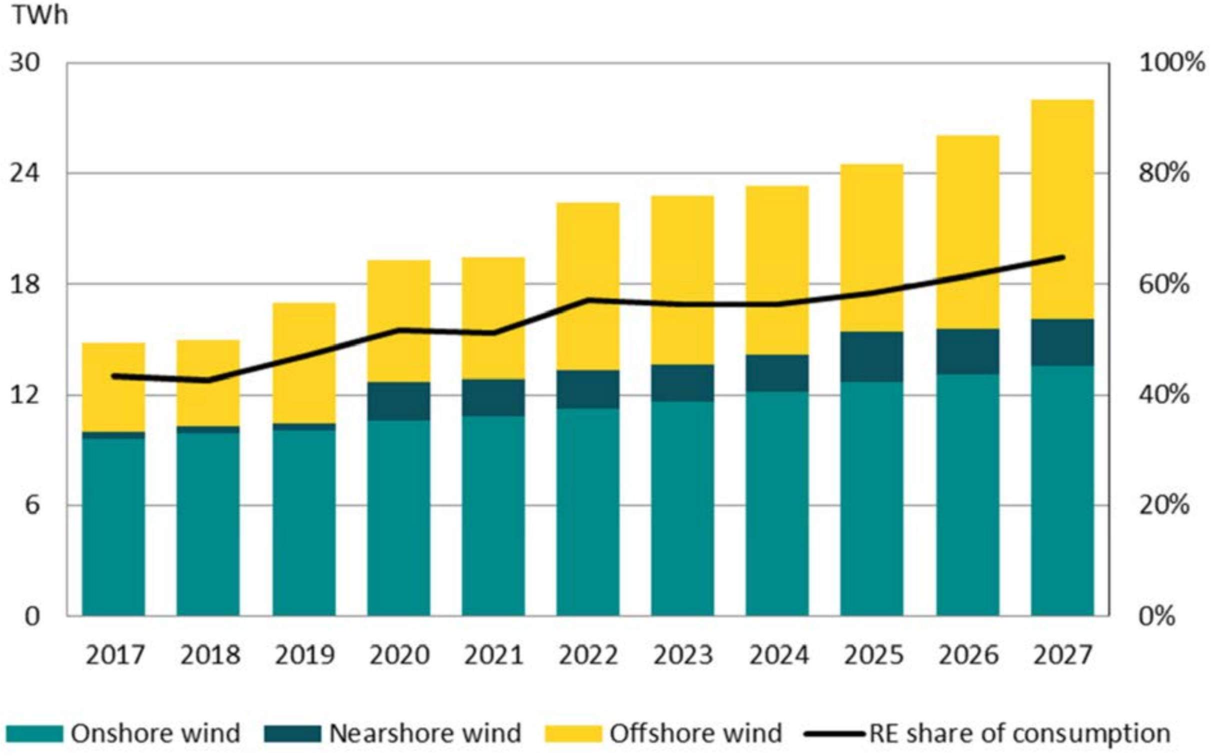
RES and non-RES as a share of the net total annual additions

Chapter 01 in Renewable energy devices and systems with simulations in MATLAB and ANSYS, Editors: F. Blaabjerg and D.M. Ionel, CRC Press LLC, 2017

IRENA, REN 21

Energy and Power Challenge in DK

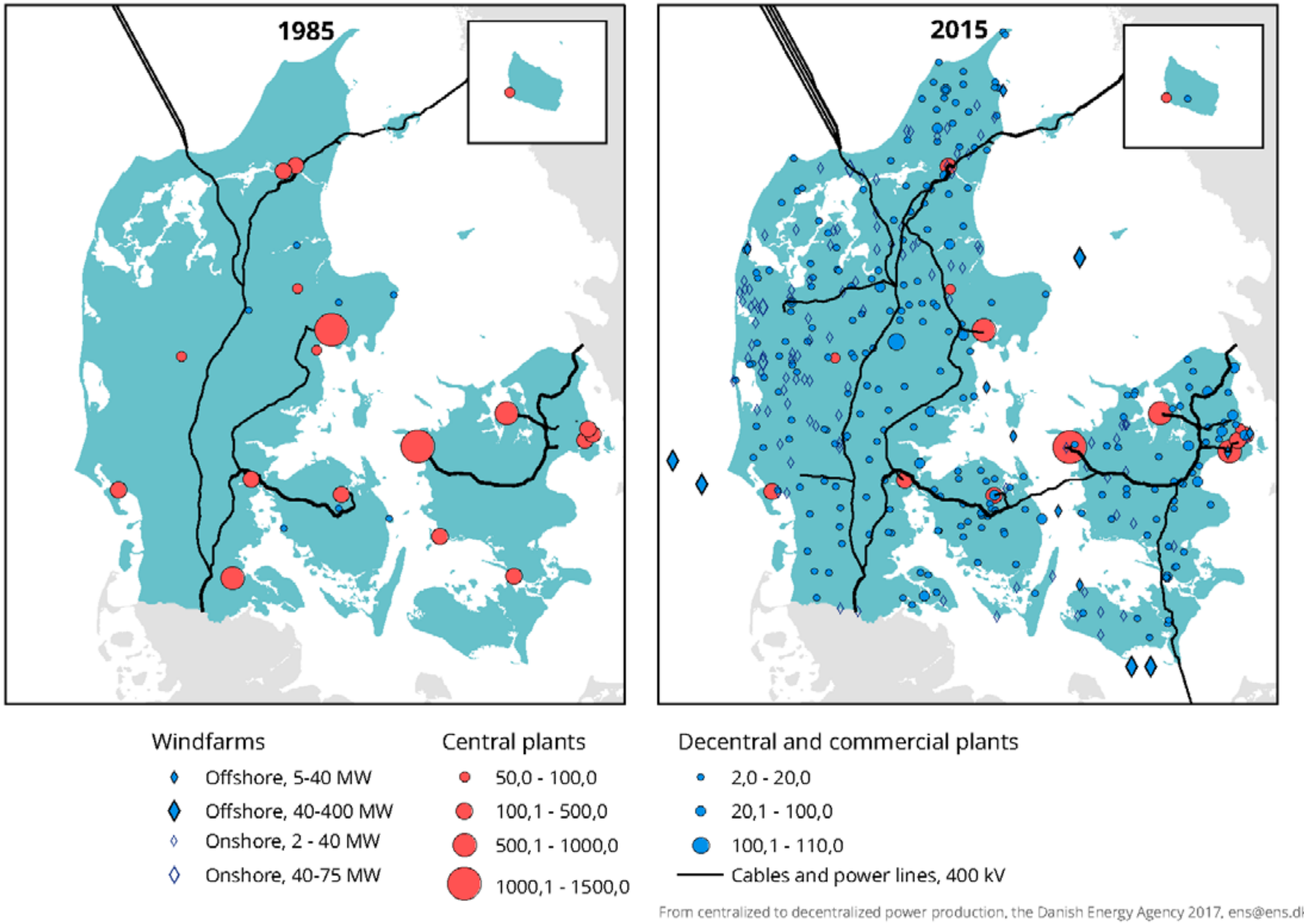
Wind power generation 2017-2027



Very High Penetration of Wind

https://en.energinet.dk/About-our-reports/Reports/Environmental-Report-2018

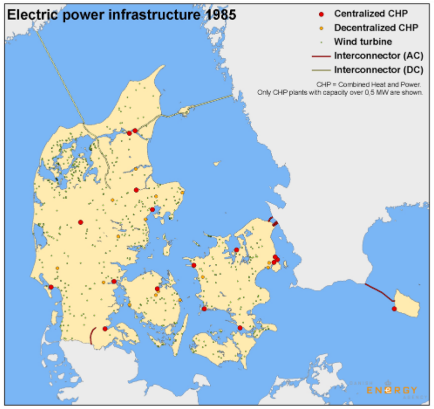
Development of Electric Power System in Denmark



From Central to De-central Power Generation

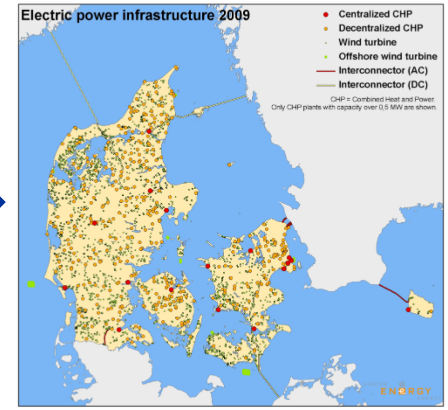
Danish Energy Agency, https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/energy-infomaps

Transition of Energy System



(Source: Danish Energy Agency)

from Central to De-central Power Generation



(Source: Danish Energy Agency)

Source: http://electrical-engineering-portal.com

from large synchronous generators to more power electronic converters

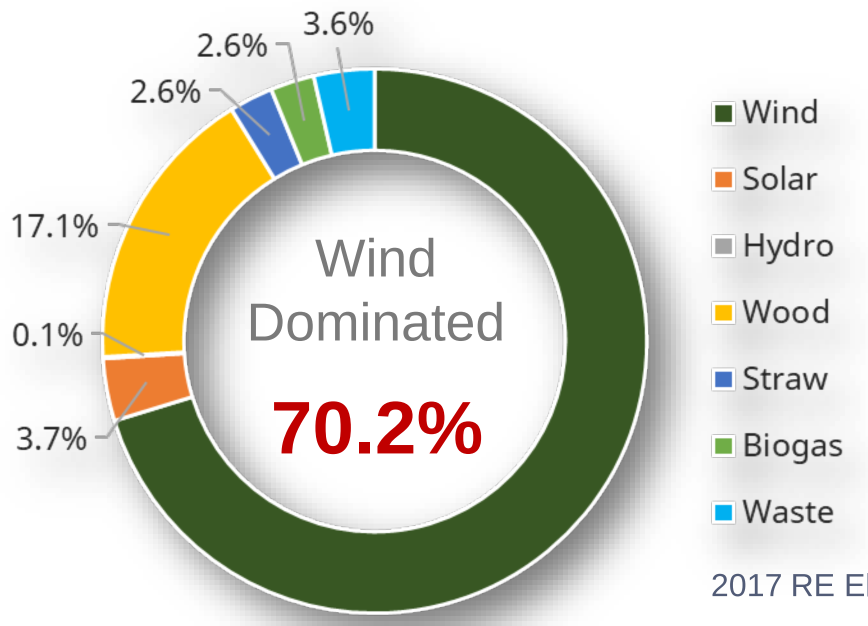
Source: http://media.treehugger.com

Towards 100% Power Electronics Interfaced

Integration to electric grid
Power transmission
Power distribution
Power conversion
Power control

Source: www.offshorewind.biz

Renewable Electricity in Denmark



2017 RE Electricity Gener. in DK

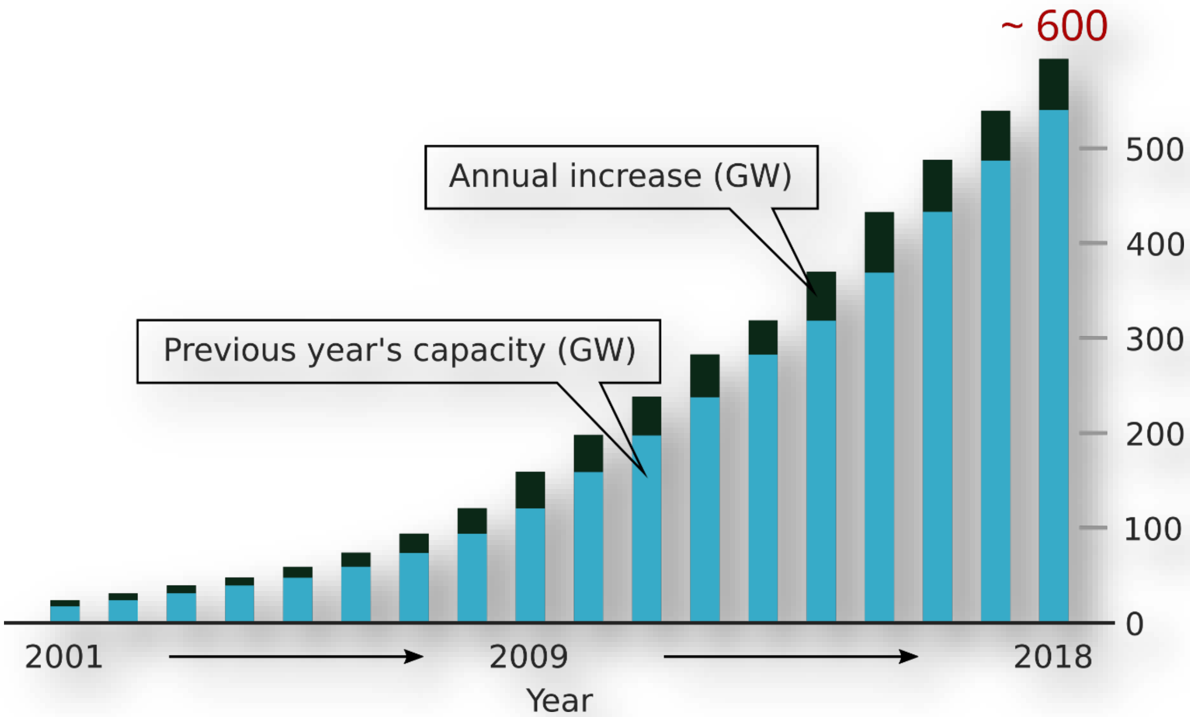
Proportion of renewable electricity in Denmark (*target value)

Key figures	2016	2017	2027	2035
Wind share of net generation in year	44.2%	50.2%	60%*	
Wind share of consumption in year	37.6%	43.4%		
RE share of net generation in year	61.6%	71.4%	90%*	100%*
RE share of consumption in year	52.4%	61.9%		

https://en.energinet.dk/About-our-reports/Reports/Environmental-Report-2018

https://ens.dk/sites/ens.dk/files/Analyser/denmarks_energy_and_climate_outlook_2017.pdf

State of the Art Development – Wind Power

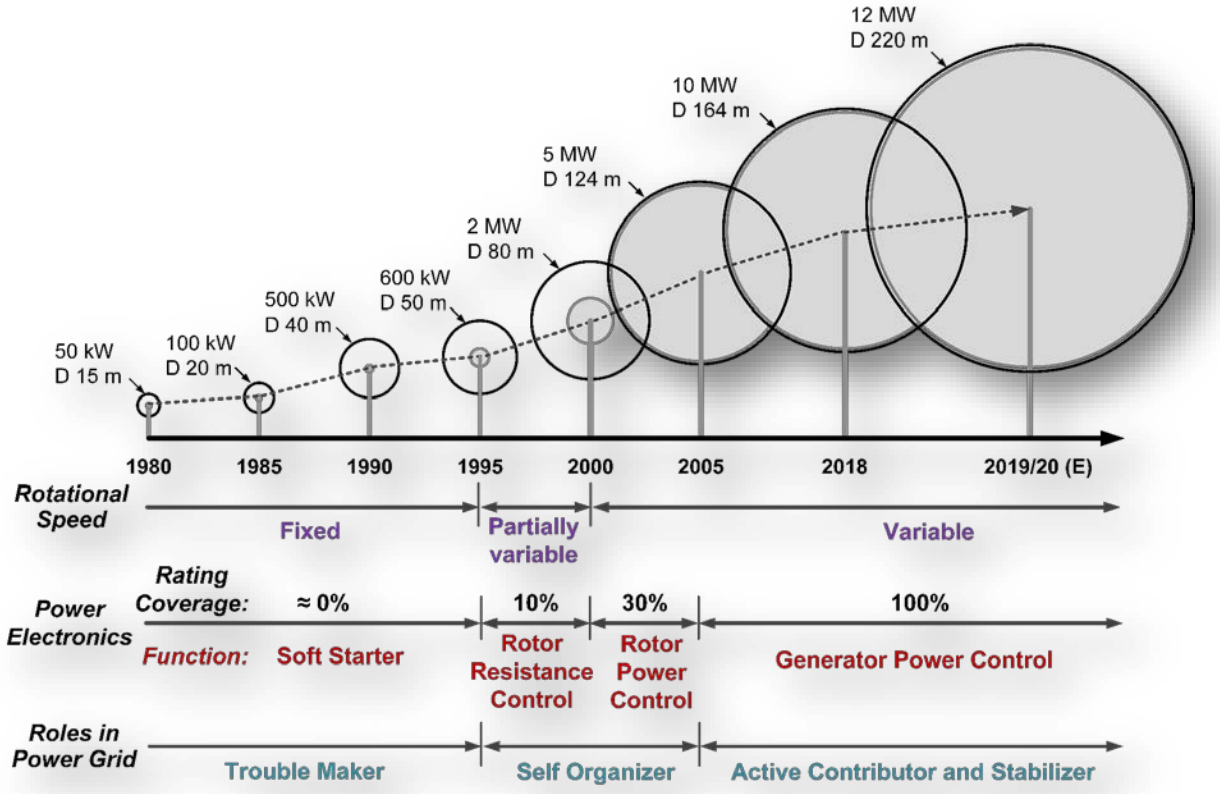


Global installed wind capacity (until 2018): 594 GW, 2018: 53.9 GW

- Higher total capacity (+50% non-hydro renewables).
- Larger individual size (average 1.8 MW, up to 6-8 MW, even 10 MW).
- More power electronics involved (up to 100 % rating coverage).

http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf
https://wwindea.org/information-2/information/

State of the Art Development – Wind Power



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http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf
https://wwindea.org/information-2/information/

Top 5 Wind Turbine Manufacturers & Technologies

Manufacturer	Concept	Rotor Diameter	Power Range
Vestas (Denmark)	DFIG PMSG	90 - 120 m 105 - 162 m	2.0 - 2.2 MW 3.4 – 9.5 MW
Siemens Gamesa (Spain)	SCIG PMSG DFIG	154 – 167 m 120 – 142 m 114 -145 m	6.0 – 8.0 MW 3.5 – 4.3 MW 2.1 – 4.5 MW
Goldwind (China)	PMSG	-	2.0 – 6.0 MW
GE (USA)	DFIG PMSG	116 – 158 m 150 m	2.0 – 5.0 MW 6.0 MW
Enercon (Germany)	WRSG	82 – 138 m	2.0 – 4.2 MW

DFIG: Doubly-Fed Induction Generator

PMSG: Permanent Magnet Synchronous Generator

SCIG: Squirrel-Cage Induction Generator

WRSG: Wound Rotor Synchronous Generator

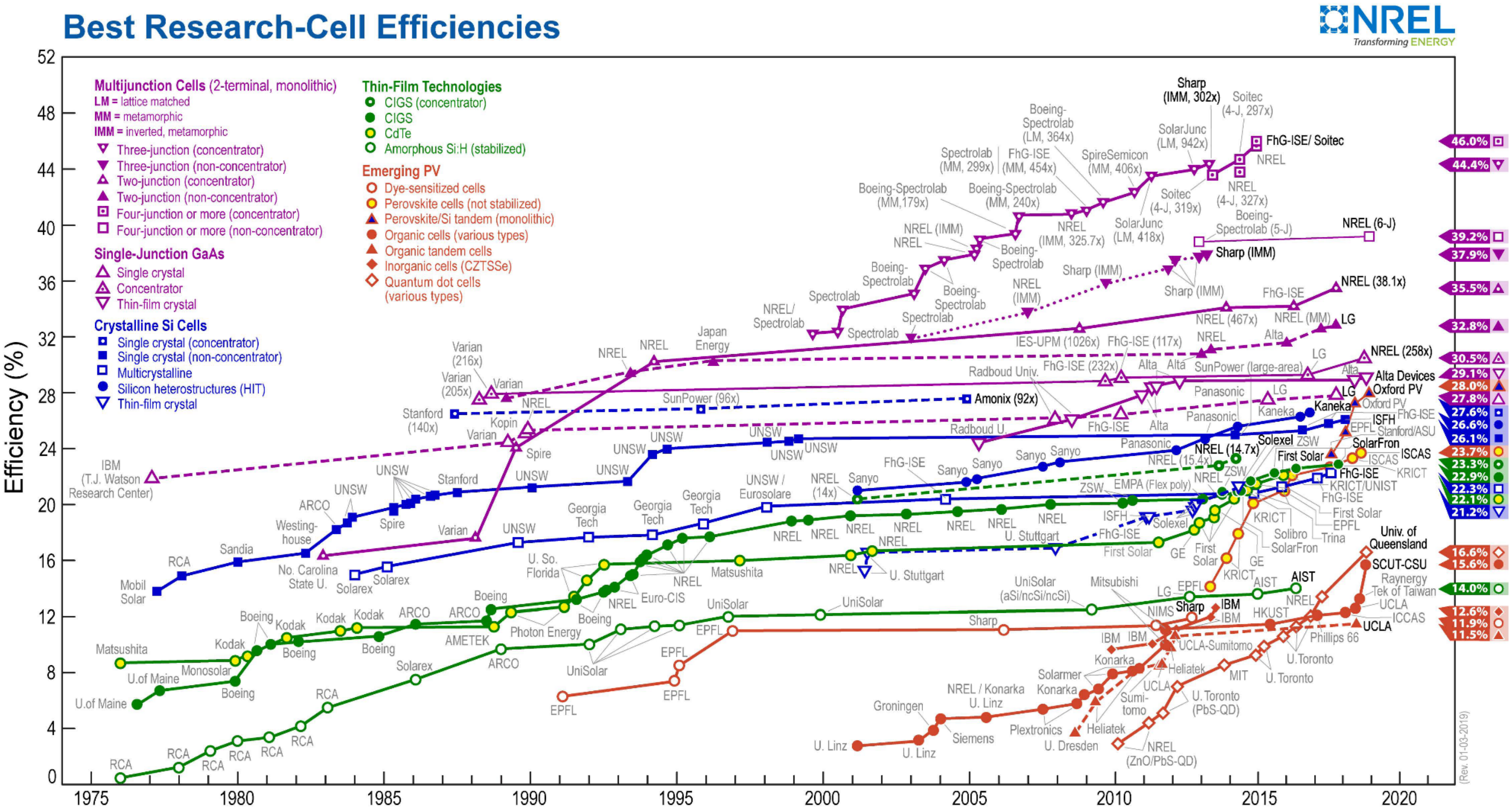
Top 10 Wind Turbine Manufacturers in the World (2018); https://www.bizvibe.com/blog/top-10-wind-turbine-manufacturers-world/

Top 10 Biggest Turbines

Manufacturer	Power Rating (MW)	Rotor Diameter (m)	Drivetrain	IEC Class
MHI Vestas	9.5	164	Medium-speed geared	S
Siemens Gamesa	8 (10)	167	Direct drive	S (IB)
Goldwind	6.7	154	PM direct drive	I
Senvion	6.15	152	High-speed geared	S
GE	6 (12)	150	Direct drive	IB
Ming Yang	6	140	Medium-speed geared	IIB
Doosan	5.5	140	High-speed geared	I
Hitachi	5.2	126-136	Medium-speed geared	S
Haizhuang	5	151	High-speed geared	IIB
Adwen	5	135	Low-speed geared	IA

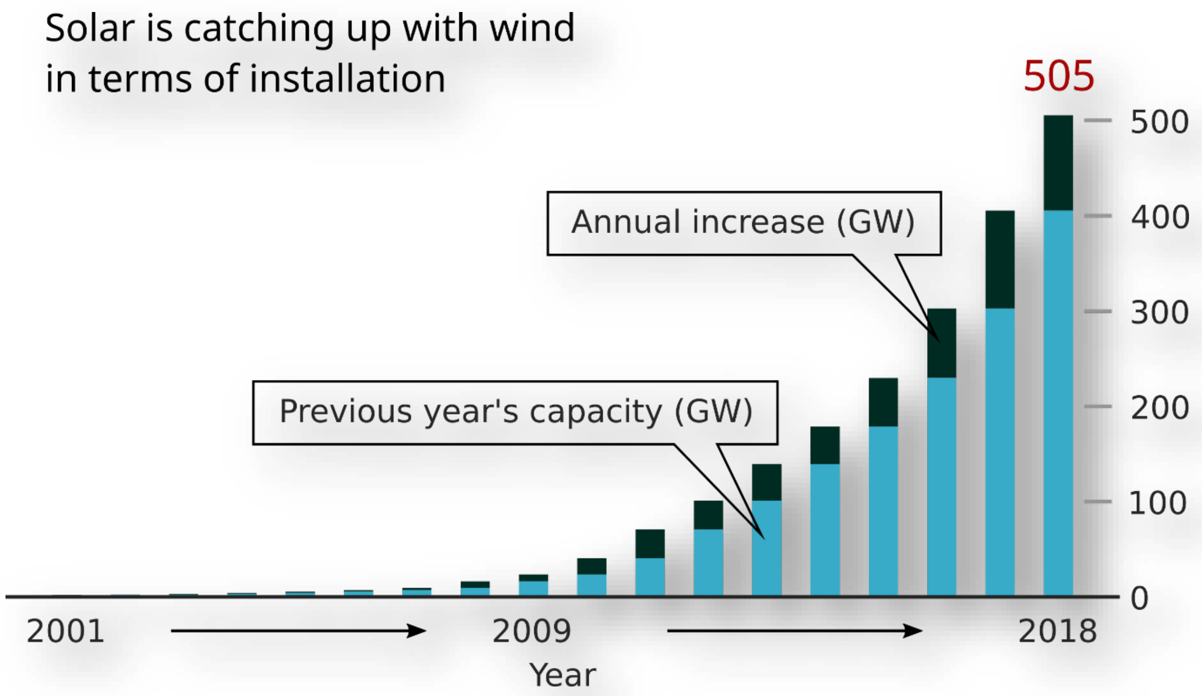
Wind Power, Ten of the Biggest Turbines, 3 Sept. 2018, https://www.windpowermonthly.com/10-biggest-turbines

State of the Art – PV Cell Technologies



National Renewable Energy Laboratory, http://www.nrel.gov/pv/assets/images/efficiency_chart.jpg

State of the Art Development – Photovoltaic Power



Global installed solar PV capacity (until 2018): 505 GW, 2018: 100 GW

- More significant total capacity (29 % non-hydro renewables).
- Fastest growth rate (42 % between 2010-2015).

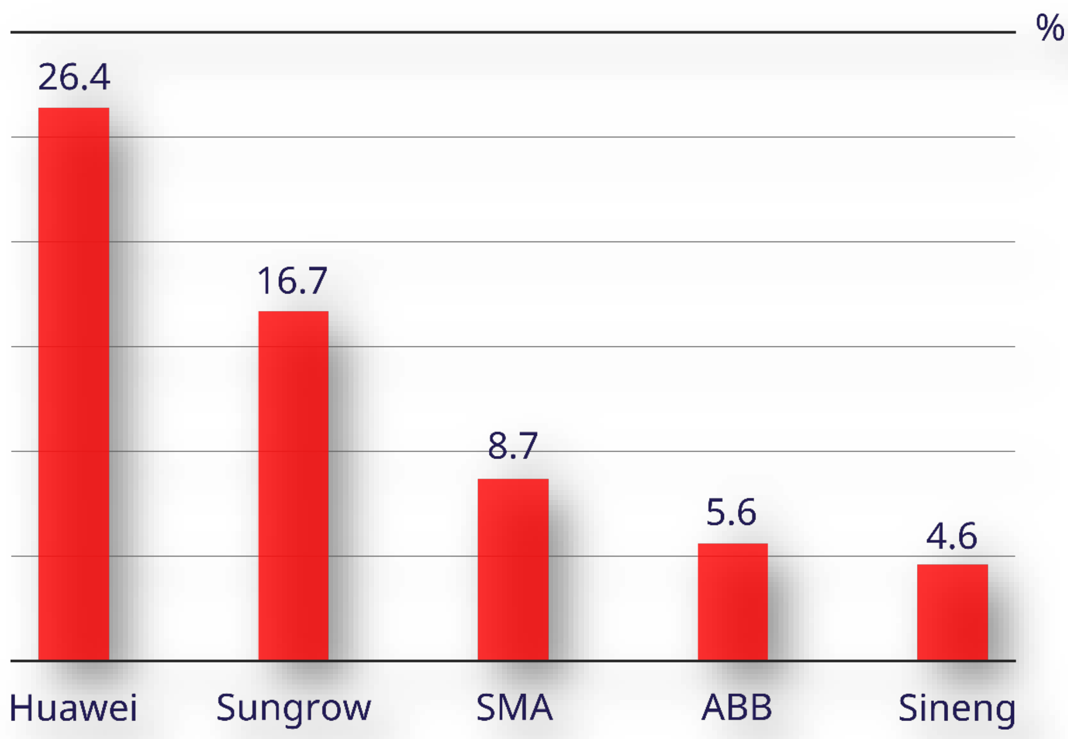
SolarPower Europe, http://www.solarpowereurope.org/home/
REN21, Renewables 2016, http://www.ren21.net/wp-content/uploads/2016/10/REN21_GSR2016_FullReport_en_11.pdf
https://en.wikipedia.org/wiki/Growth_of_photovoltaics
http://www.iea-pvps.org/fileadmin/dam/public/Press_Releases/Press_Release_T1_15042019_-_Snapshot.pdf

Top 10 Solar PV Manufacturers to Watch in 2018

Manufacturer	Global Installation	Remarks
Canadian Solar	24 GW	High power output
Trina Solar	11 GW	Focusing on panel efficiency
First Solar	17 GW	Thin film tech
Jinko Solar	18 GW	Monocrystalline tech, 23.5% η
JA Solar	23 GW	Mass production about 5 to 10 watts above industry average, floating PV form supplier
Sun Power Corp	18 GW	Residential, commercial, utility; Cradle to grave certified
LG Energy	-	Energy production from both sides
Winaico	-	Mono-/polycrystalline tech for harsh conditions, e.g., salt spray
Hanwha Q Cells	-	Patented Q.ANTUM tech enhancing panel energy yield in low light
Mitsubishi Electric	-	No lead solder, re-usable, biodegradable materials

Damon Lapping, Top 10 Solar PV Manufacturers to Watch in 2018, https://www.disruptordaily.com/top-10-solar-pv-manufacturers-watch-2018/

Top 5 PV Inverter Supplier



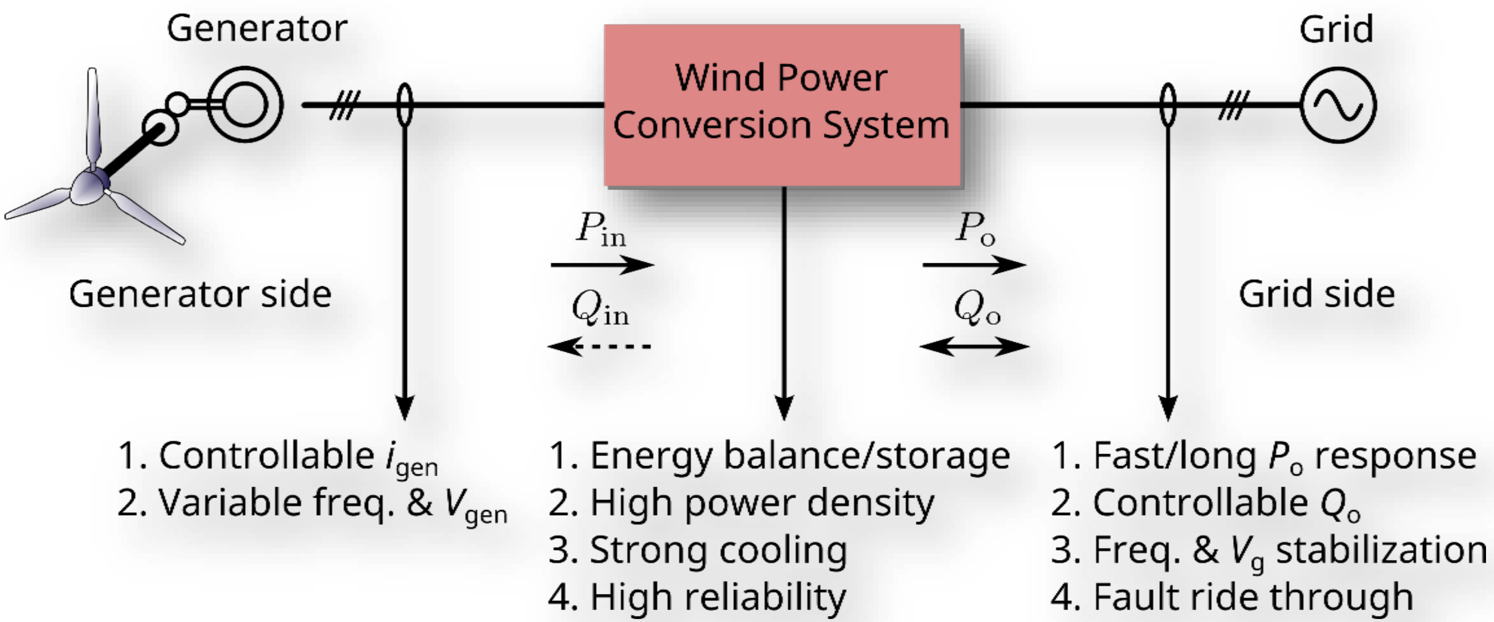
Global Market Share (%) of Top Five PV Inverter Suppliers by Shipments (MWac) in 2017

Figure Adapted according to the GTM Research report

PV Europe, https://www.pveurope.eu/News/Solar-Generator/Solar-inverter-ranking-Huawei-Sungrow-and-SMA-leading

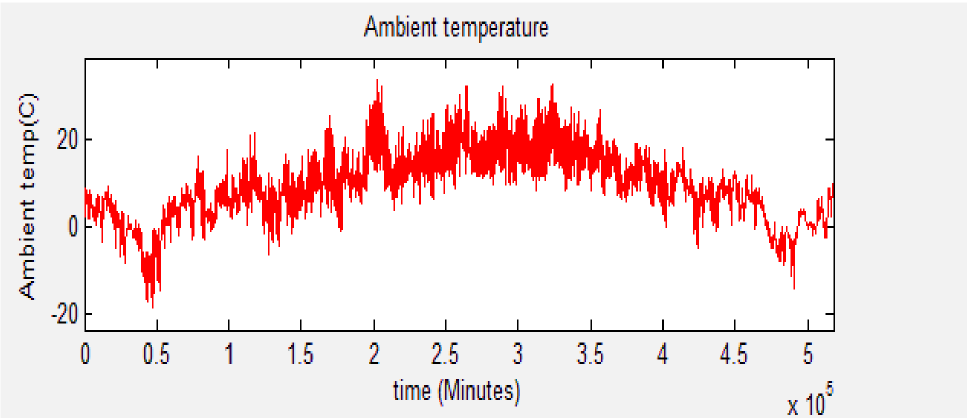
Demands for renewable energy systems

Requirements for Wind Turbine Systems

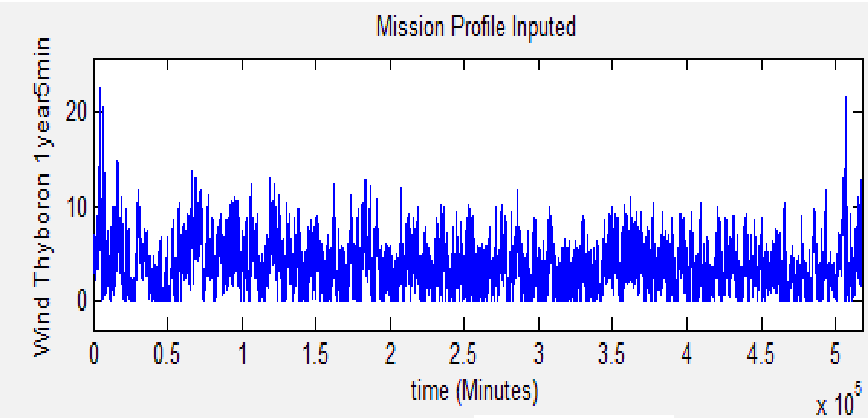


General Requirements & Specific Requirements

Input mission profiles for wind power application



Ambient temperature



Wind speed

Mission profile for wind turbines in Thyboron wind farm

- Highly variable wind speed
- Different wind classes are defined - turbulence and avg. speed
- Large power inertia to wind speed variation – stored energy in rotor.
- Large temperature inertia to ambient temp. variation – large nacelle capacity

Grid Codes for Wind Turbines

Conventional power plants provide active and reactive power, inertia response, synchronizing power, oscillation damping, short-circuit capability and voltage backup during faults.

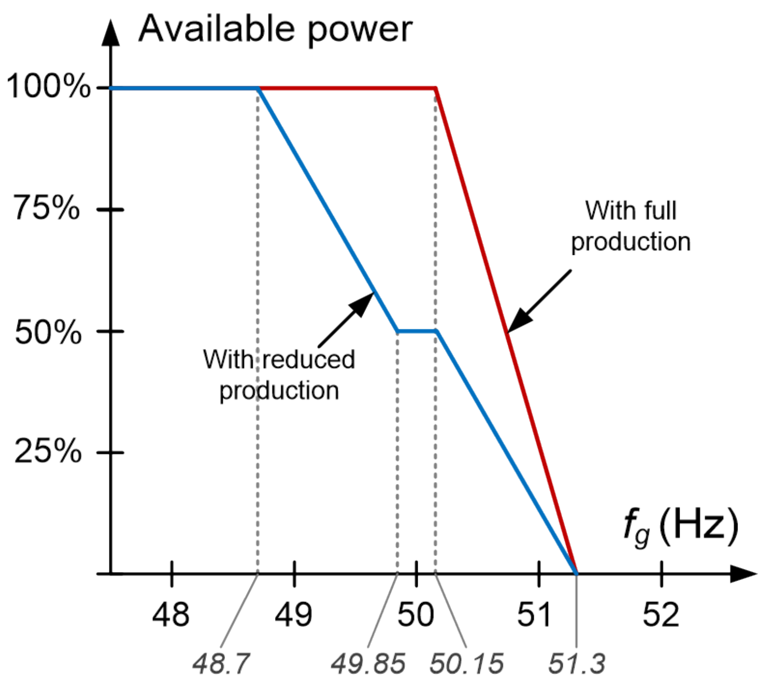
Wind turbine technology differs from conventional power plants regarding the converter-based grid interface and asynchronous operation

Grid code requirements today

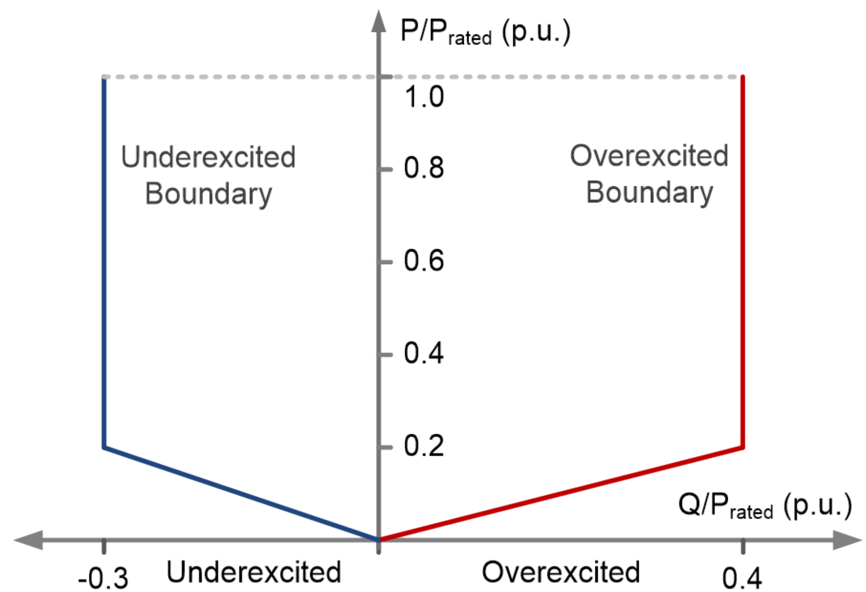
- Active power control
- Reactive power control
- Frequency control
- Steady-state operating range
- Fault ride-through capability

Wind turbines are active power plants.

Power Grid Standards – Frequency/Voltage Support



Freq. – P control

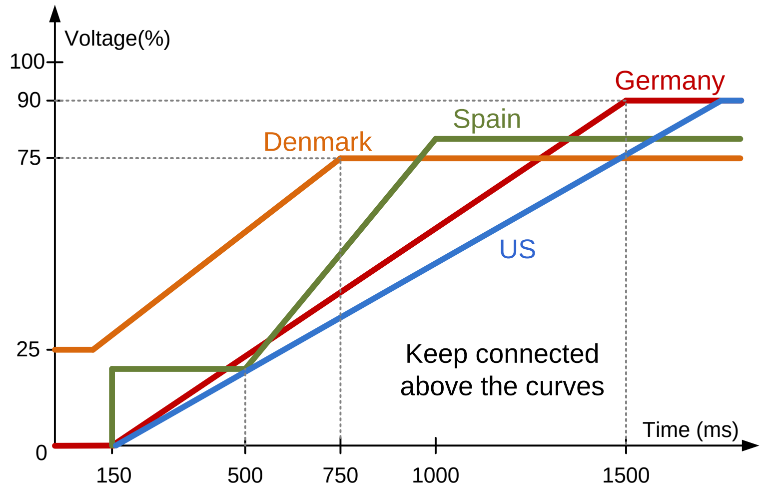


Q ranges under different generating *P*

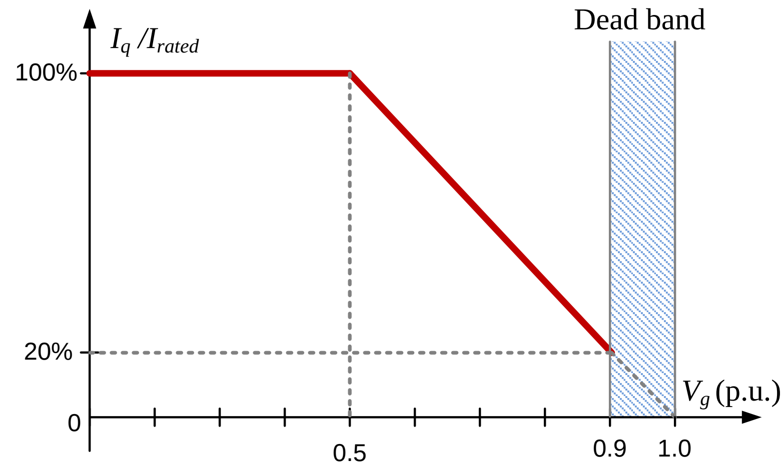
- Frequency control through active power regulation.
- Reactive power control according to active power generation.
- Voltage support through reactive power control.

Power Grid Standards – Ride-Through Operation

Requirements during grid faults



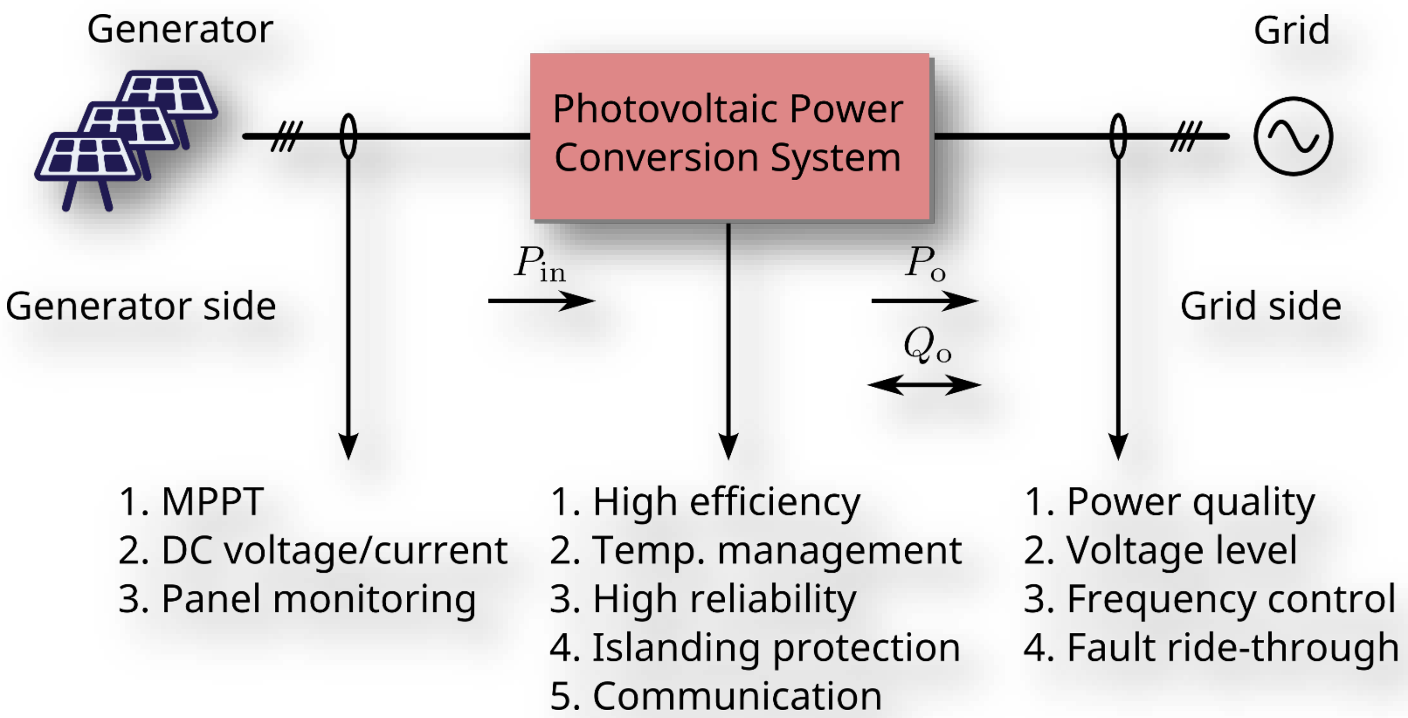
Grid voltage dips vs. withstand time



Reactive current vs. Grid voltage dips

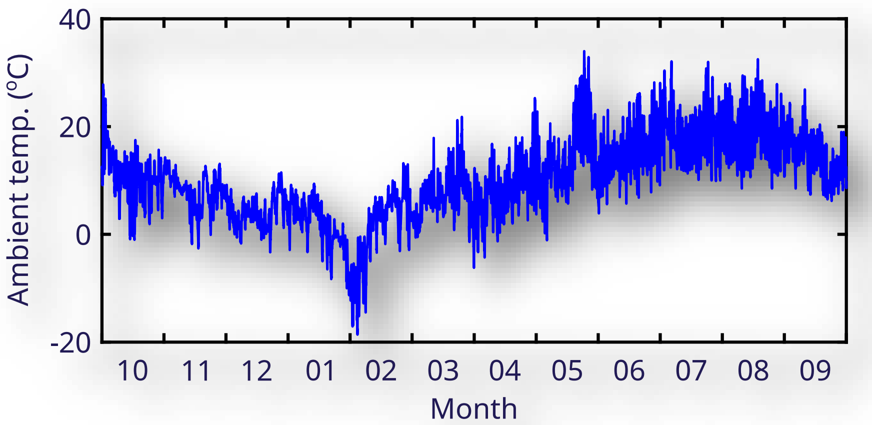
- Withstand extreme grid voltage dips.
- Contribute to grid recovery by injecting I_q.
- Higher power controllability of converter.

Requirements for Photovoltaic Systems

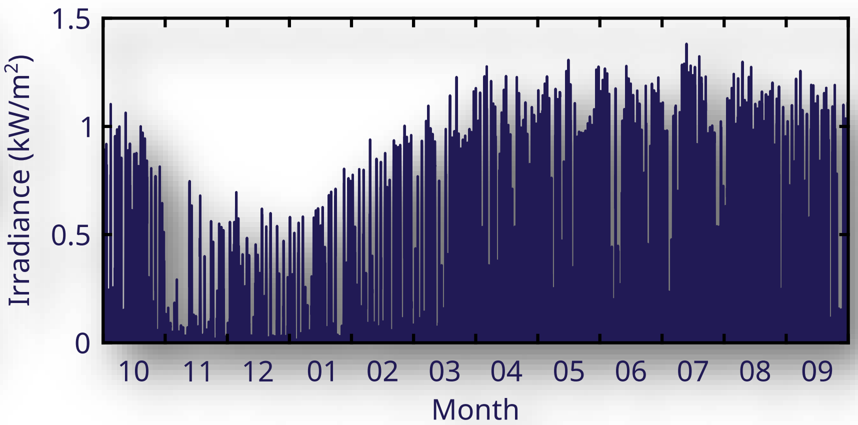


General Requirements & Specific Requirements

Input mission profiles for PV power application



Ambient temperature



Solar irradiance

Mission Profile for PV Systems Measured at AAU (201110-201209)

- Highly variable solar irradiance
- Small power inertia to solar variation – quick response of PV panel.
- Small temperature inertia to ambient temp. variation – small case capacity.
- Temperature sensitive for the PV panel and power electronics.

Grid Codes for Photovoltaic Systems

Grid-connected PV systems ranging from several kWs to even a few MWs are being developed very fast and will soon take a major part of electricity generation in some areas. PV systems have to comply with much tougher requirements than ever before.

Requirements today

- Maximize active power capture (MPPT)
- Power quality issue
- Ancillary services for grid stability
- Communications
- High efficiency

In case of large-scale adoption of PV systems

- Reactive power control
- Frequency control
- Fault ride-through capability
- …

Catering for Lower PV Energy Cost

A pathway toward the 2020 SunShot goal:

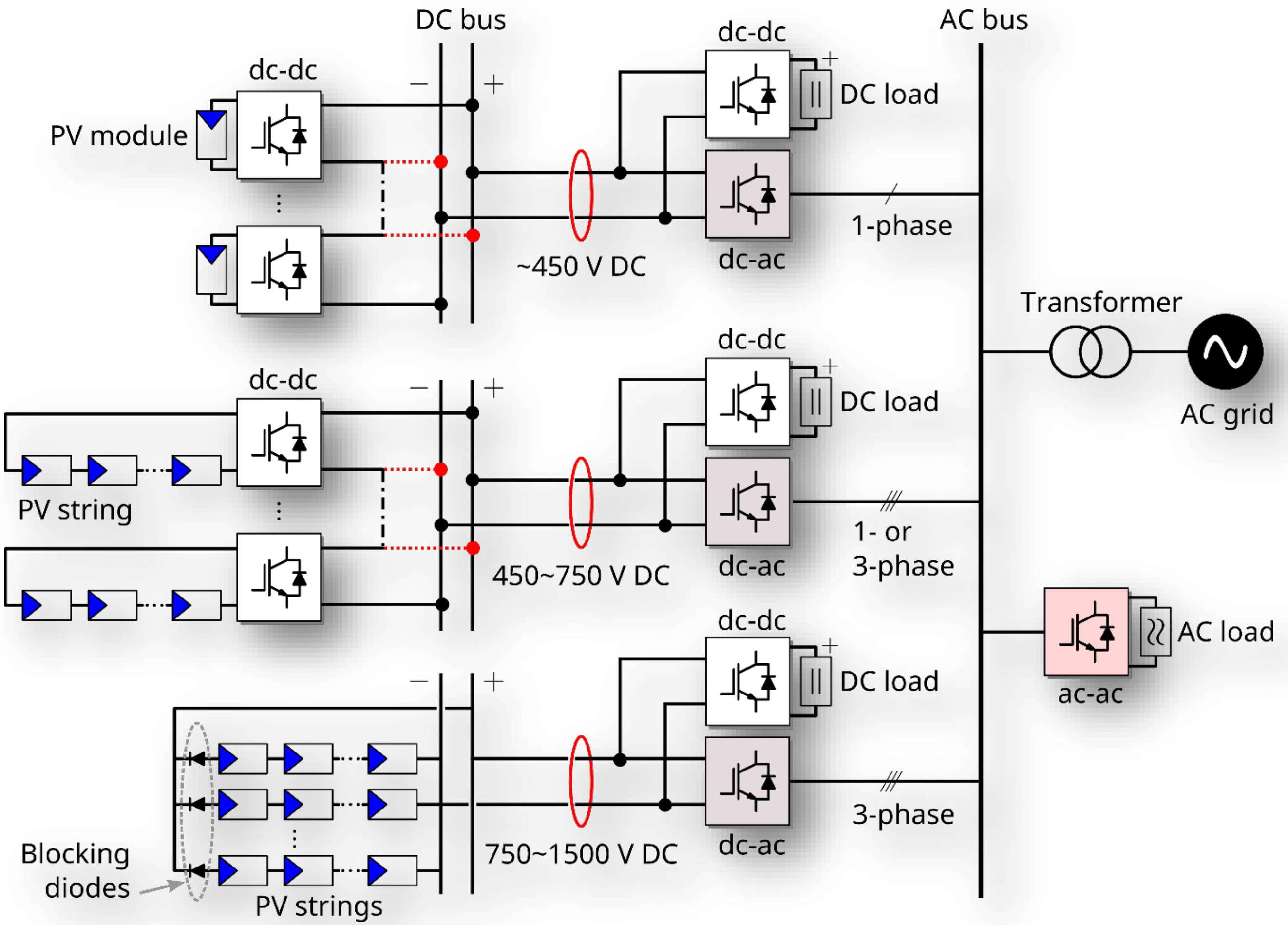
Parameter	2015	SunShot 2020
Degradation rate (%/year)	0.75	0.2
DC-to-AC power ratio	1.4	1.4
Total DC and AC power losses (%)	4.5 and 2.0	4.5 and 2.0
Inverter lifetime (years)	15 years	30 years
Inverter replacement ($/Watt)	0.15 $	-

- ❑ LCOE: 10 cents/kWh → 6 cents/kWh
- ❑ PV module degradation rate: 0.75 % → 0.2 %
- ❑ Inverter lifetime should be double (no inverter replacement)

R. Jones-Albertus, D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse, “Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity,” Prog. Photovoltaics Res. Appl., 2016.

Power converters for renewables application

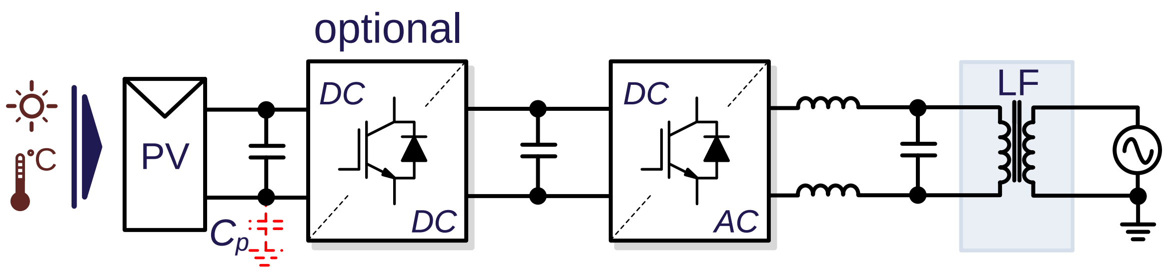
PV Inverter System Configurations

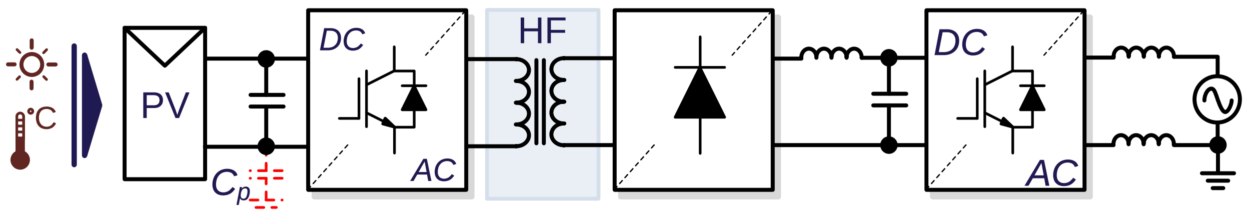


Module Converters | String Inverter | Multi-String Inverters | Central Inverters

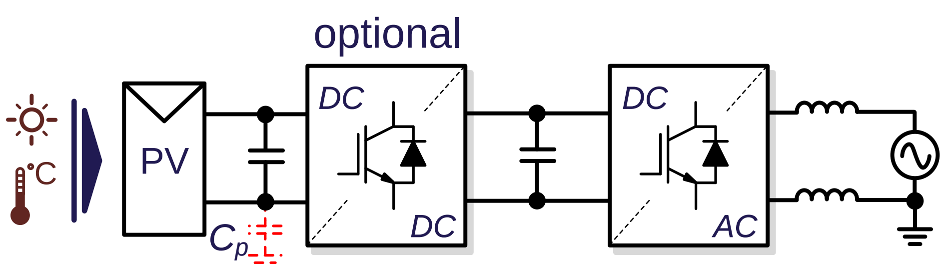
Grid-Connection Configurations

Transformer-based grid-connection





Transformerless grid-connection → Higher efficiency, Smaller volume

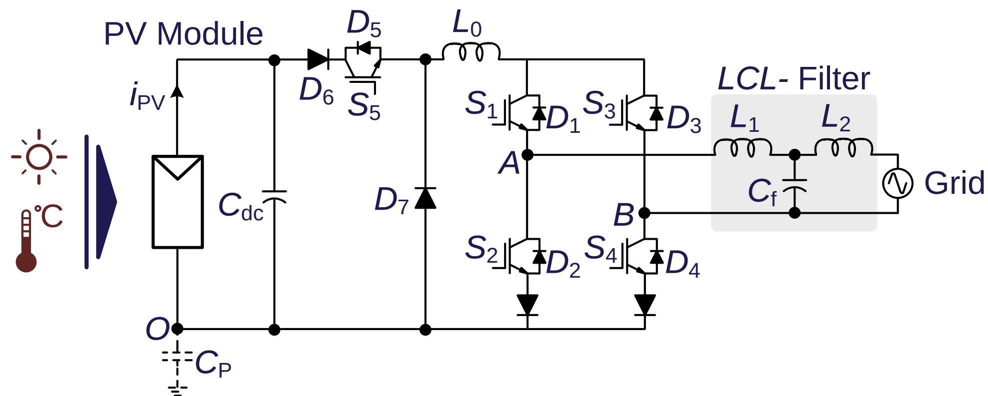


AC-Module PV Converters – Single-Stage

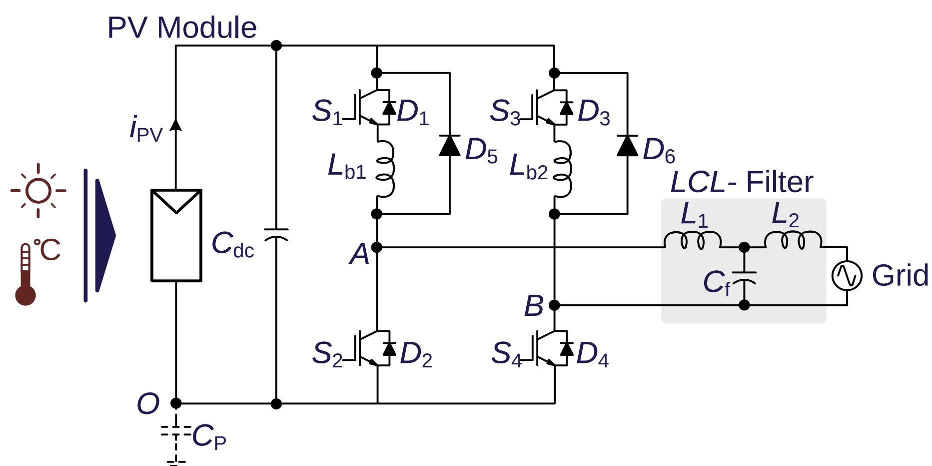
~ 300 W (several hundred watts)

High overall efficiency and High power desity.

Universal AC-module inverter



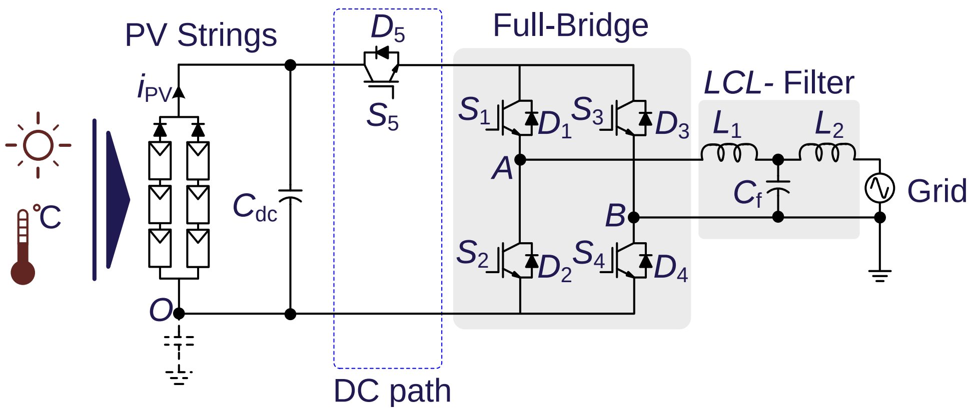
Buck-boost integrated full-bridge inverter



B.S. Prasad, S. Jain, and V. Agarwal, "Universal Single-Stage Grid-Connected Inverter," *IEEE Trans Energy Conversion*, 2008.
C. Wang "A novel single-stage full-bridge buck-boost inverter", *IEEE Trans. Power Electron.*, 2004.

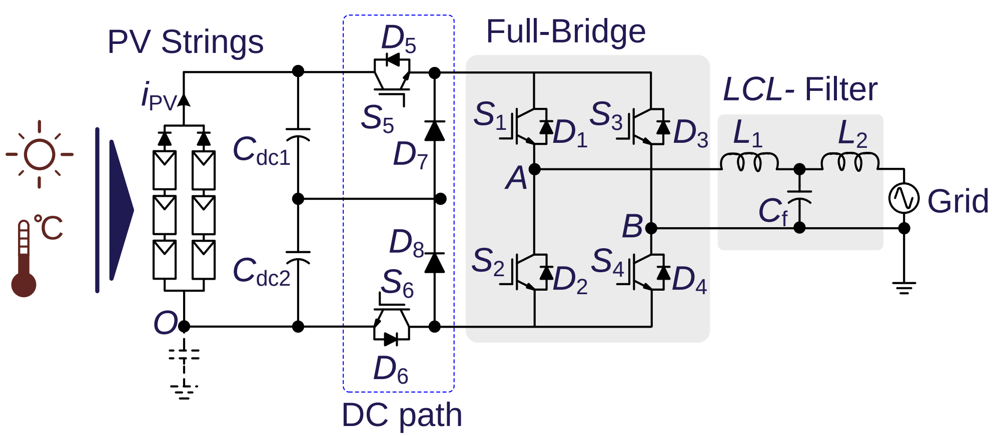
Transformerless String Inverters

H5 Transformerless Inverter (SMA)



- Efficiency of up to 98%
- Low leakage current and EMI
- Unipolar voltage accross the filter, leading to low core losses

H6 Transformerless Inverter (Ingeteam)

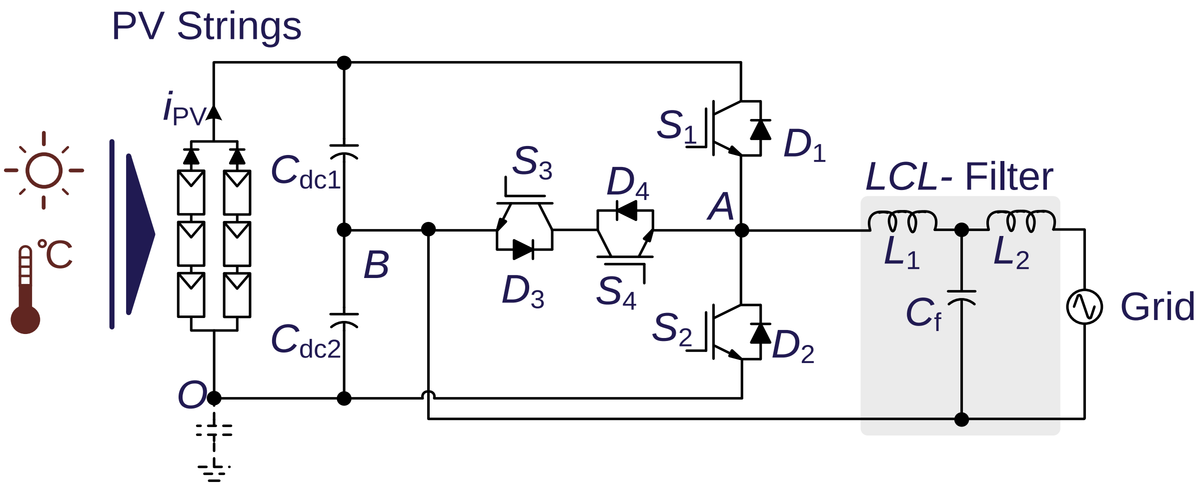


- High efficiency
- Low leakage current and EMI
- DC bypass switches rating: $V_{dc}/2$
- Unipolar voltage accross the filter

M. Victor, F. Greizer, S. Bremicker, and U. Hubler, U.S. Patent 20050286281 A1, Dec 29, 2005.
R. Gonzalez, J. Lopez, P. Sanchis, and L. Marroyo, "Transformerless inverter for single-phase photovoltaic systems," *IEEE Trans. Power Electron.*, 2007.

NPC Transformerless String Inverters

Neutral Point Clamped (NPC) converter for PV applications

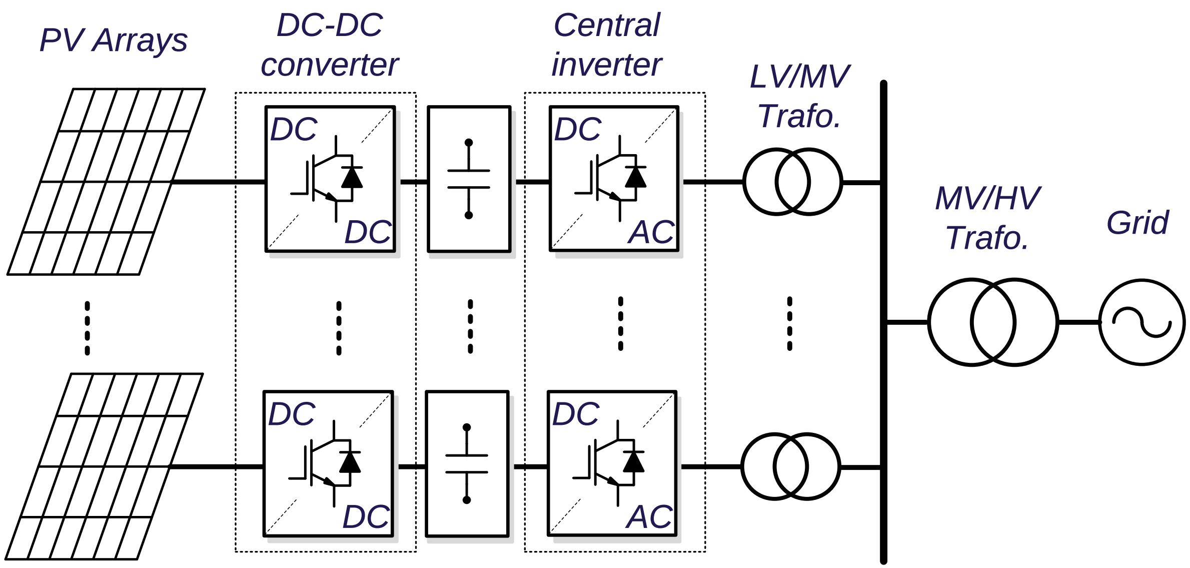


- ➢ Constant voltage-to-ground → Low leakage current, suitable for transformerless PV applications.
- ➢ High DC-link voltage (> twice of the grid peak voltage)

P. Knaup, International Patent Application, Publication Number: WO 2007/048420 A1, Issued May 3, 2007.

Central Inverters

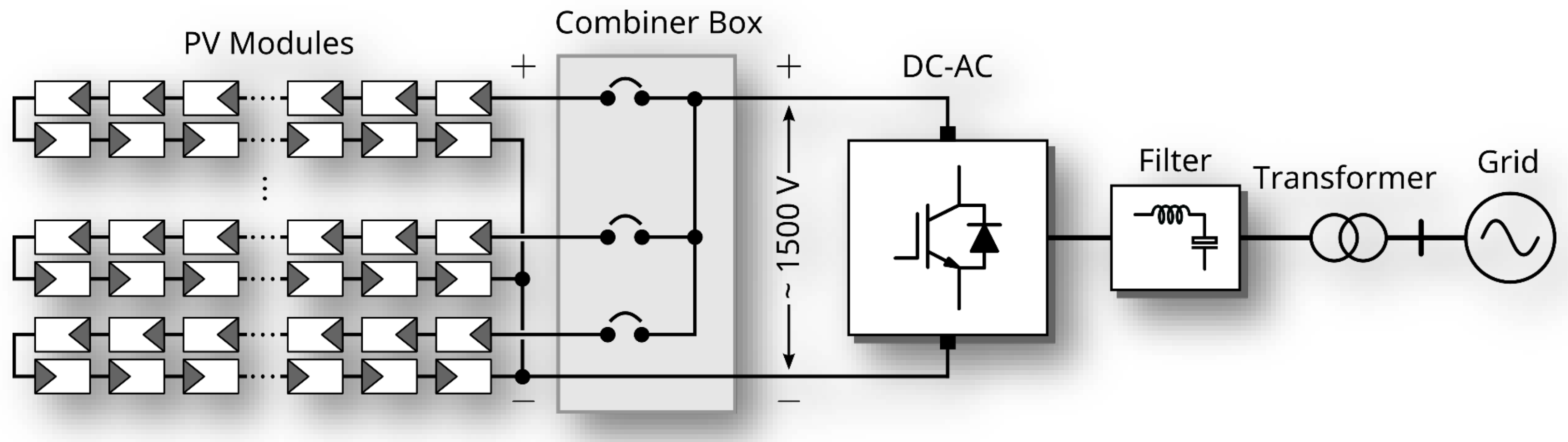
~ 30 kW (tens kilowatts to megawatts)
Very high power capacity.



- Large PV power plants (e.g. 750 kW by SMA), rated over tens and even hundreds of MW, adopt many central inverters with the power rating of up to 900 kW.
- DC-DC converters are also used before the central inverters.
- DC voltage becomes up to 1500 V
- Similar to wind turbine applications → NPC topology might be a promising solution.

1500-V DC PV System

Becoming the mainstream solution!



- Decreased requirement of the balance of system (e.g., combiner boxes, DC wiring, and converters) and Less installation efforts
- Contributes to reduced overall system cost and increased efficiency
- More energy production and lower cost of energy
- Electric safety and potential induced degradation
- Converter redesign – higher rating power devices

1500-V DC PV System

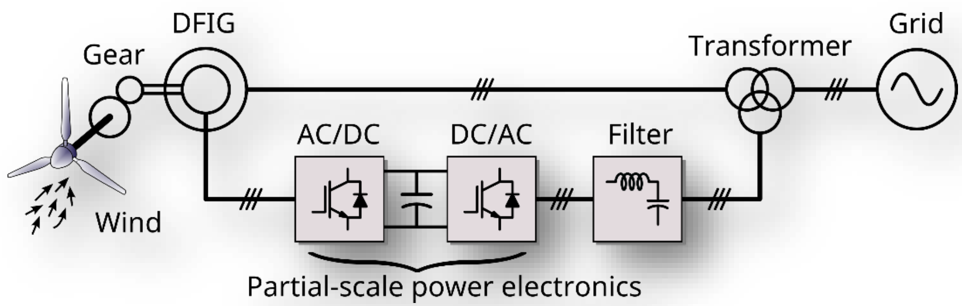
Becoming the mainstream solution!

ABB MW Solution

Sungrow five-level topology

https://www.pv-tech.org/products/abb-launches-high-power-1500-vdc-central-inverter-for-harsh-conditions
https://www.pv-tech.org/products/sungrows-1500vdc-sg125hv-string-inverter-enables-5mw-pv-power-block-designs

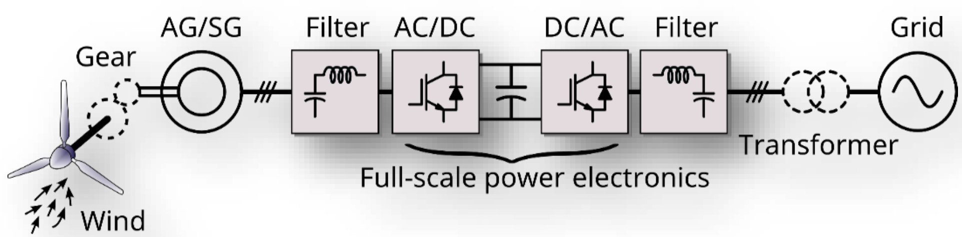
Wind turbine concept and configurations



Partial scale converter with DFIG

- Variable pitch – variable speed
- Doubly Fed Induction Generator
- Gear box and slip rings
- ±30% slip variation around synchronous speed
- Power converter (back to back/ direct AC/AC) in rotor circuit

✓ State-of-the-art solutions

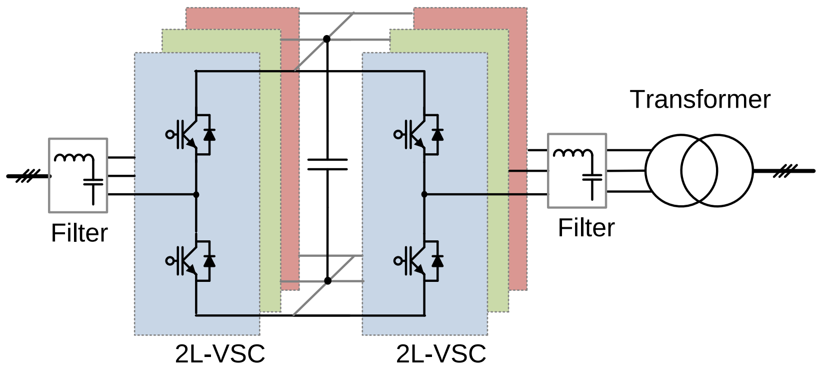


Full scale converter with SG/IG

- Variable pitch – variable speed
- Generator
  Synchronous generator
  Permanent magnet generator
  Squirrel-cage induction generator
- With/without gearbox
- Power converter
  Diode rectifier + boost DC/DC + inverter
  Back-to-back converter
  Direct AC/AC (e.g. matrix, cycloconverters)

✓ State-of-the-art and future solutions

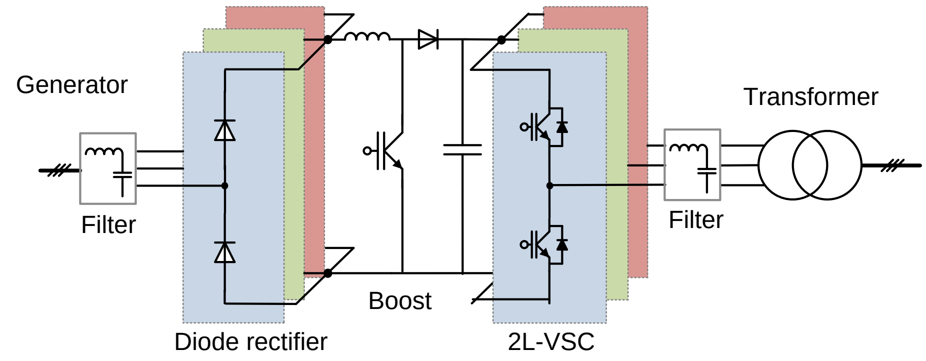
Converter topologies under low voltage (<690V)



Back-to-back two-level voltage source converter

- Proven technology
- Standard power devices (integrated)
- Decoupling between grid and generator (compensation for non-symmetry and other power quality issues)

- High dv/dt and bulky filter
- Need for major energy-storage in DC-link
- High power losses at high power (switching and conduction losses) → low efficiency

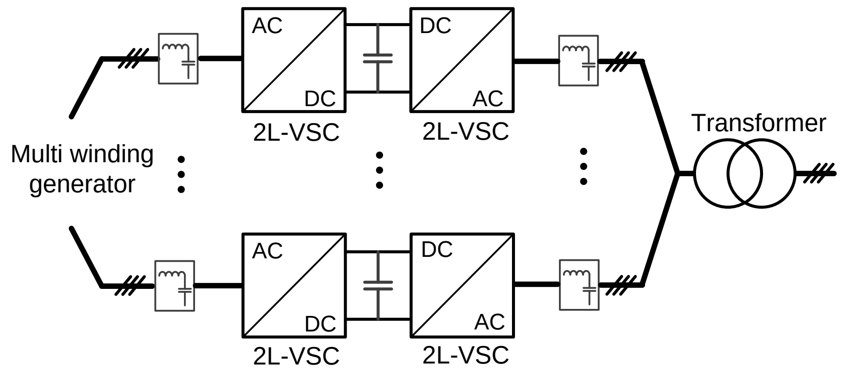


Diode rectifier + boost DC/DC + 2L-VSC

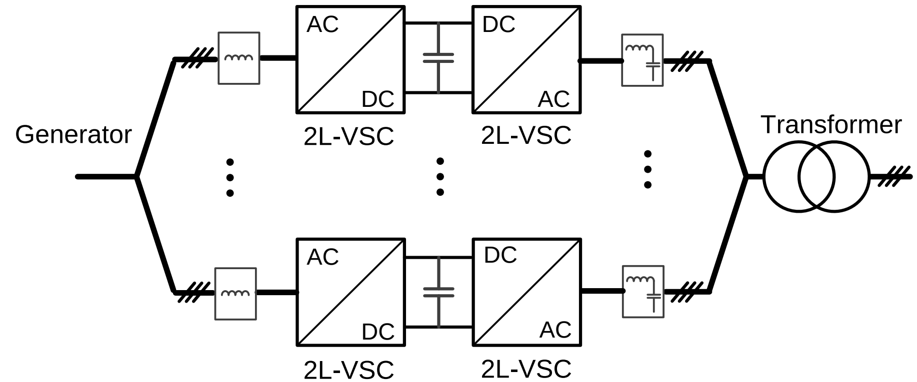
- Suitable for PMSG or SG.
- Lower cost

- Low THD on generator, low frequency torque pulsations in drive train.
- Challenge to design boost converter at MW.

Solution to extend the power capacity



Variant 1 with multi-winding generator.



Variant 2 with normal winding generator

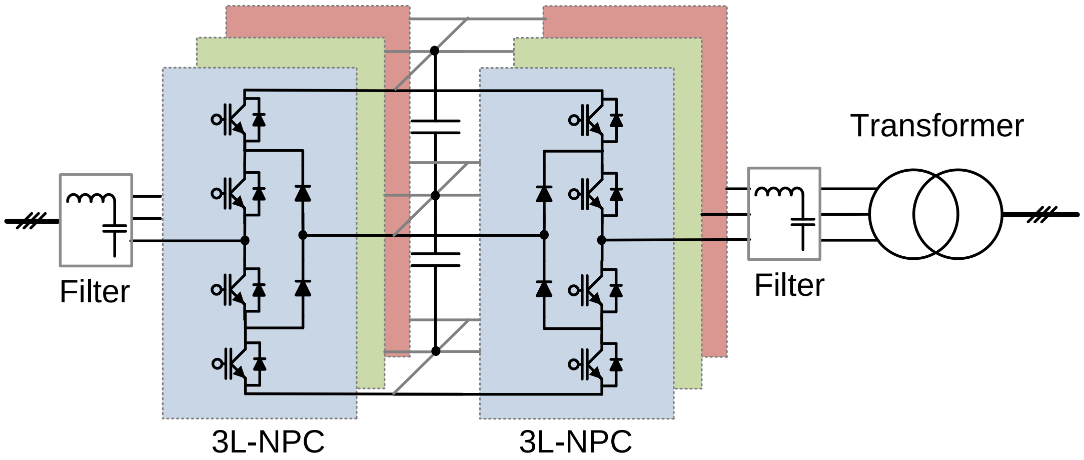
Parallel converter to extend the power capacity

- State-of-the-art solution in industry (>3MW)
- Standard and proven converter cells (2L VSC)
- Redundant and modular characteristics.

- Circulating current under common DC link with extra filter or special PWM

Multi-level converter topology – 3L-NPC

Three-level NPC



- Most commerciallized multi-level topology.
- More output voltage levels → Smaller filter
- Higher voltage, and larger output power with the same device rating
- Possible to be configured in parallel to extend power capacity.

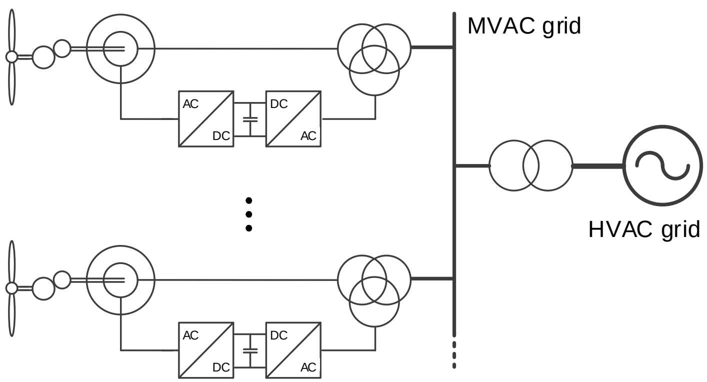
- Unequal losses on the inner and outer power devices → derated converter power capacity
- Mid-point balance of DC link – under various operating conditions.

A 400 MW off-shore Wind Power System in Denmark

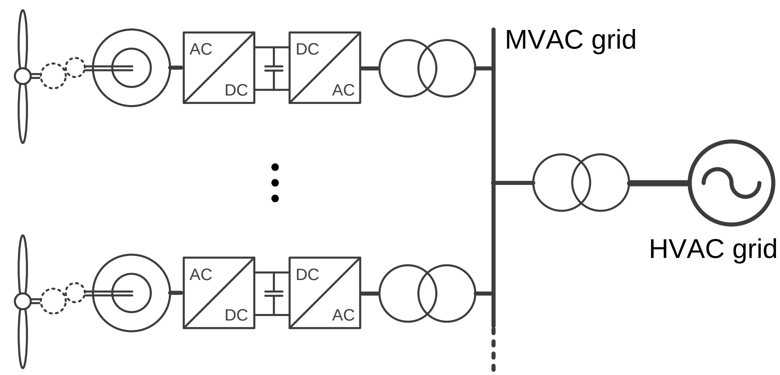
Anholt-DK (2016) – Ørsted

Wind Farm with AC and DC Power Transmission

HVAC power transmission

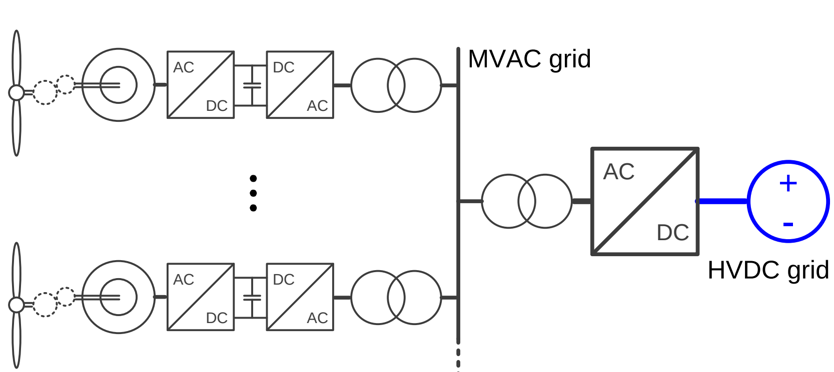


Partial-scale converter system

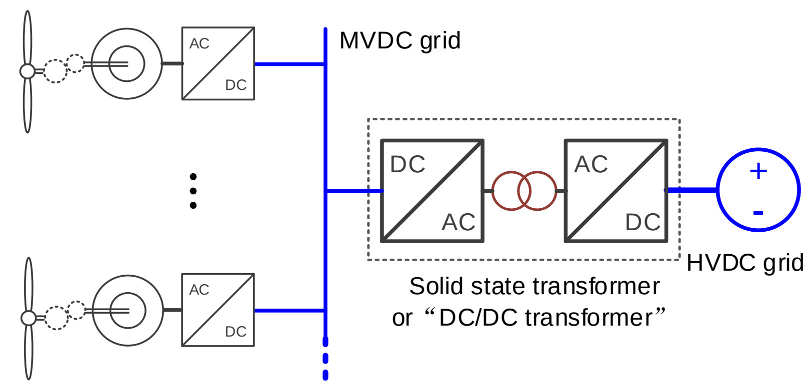


Full-scale converter system

HVDC power transmission

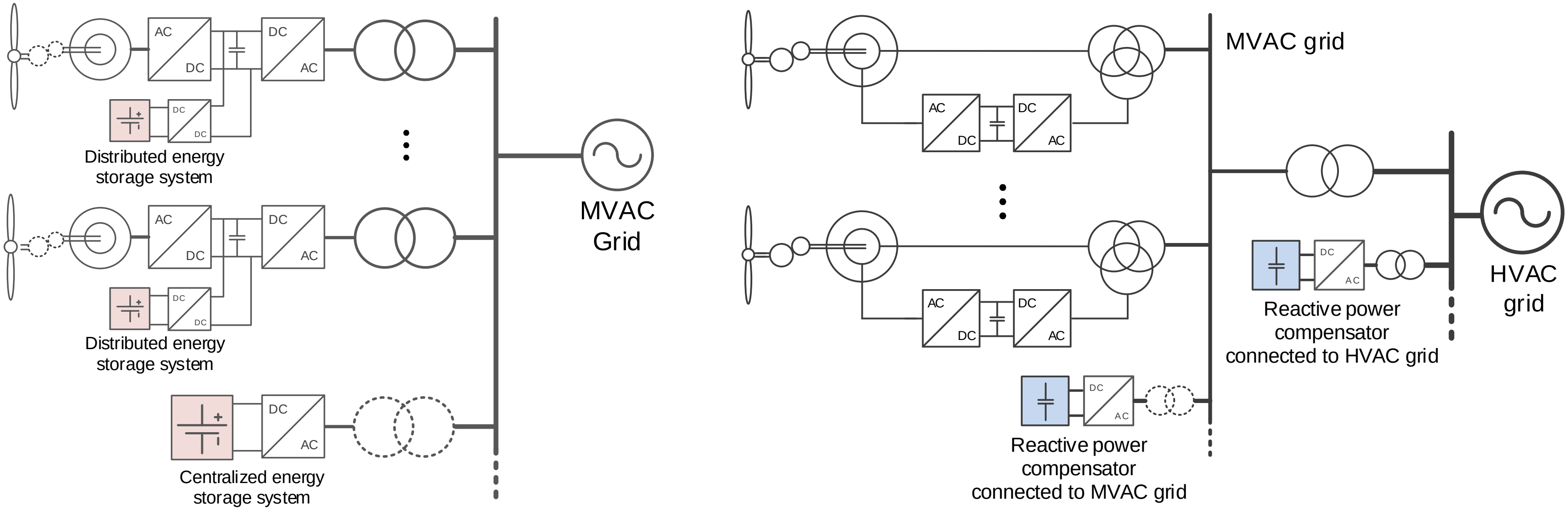


DC transmission grid



DC distribution & transmission grid

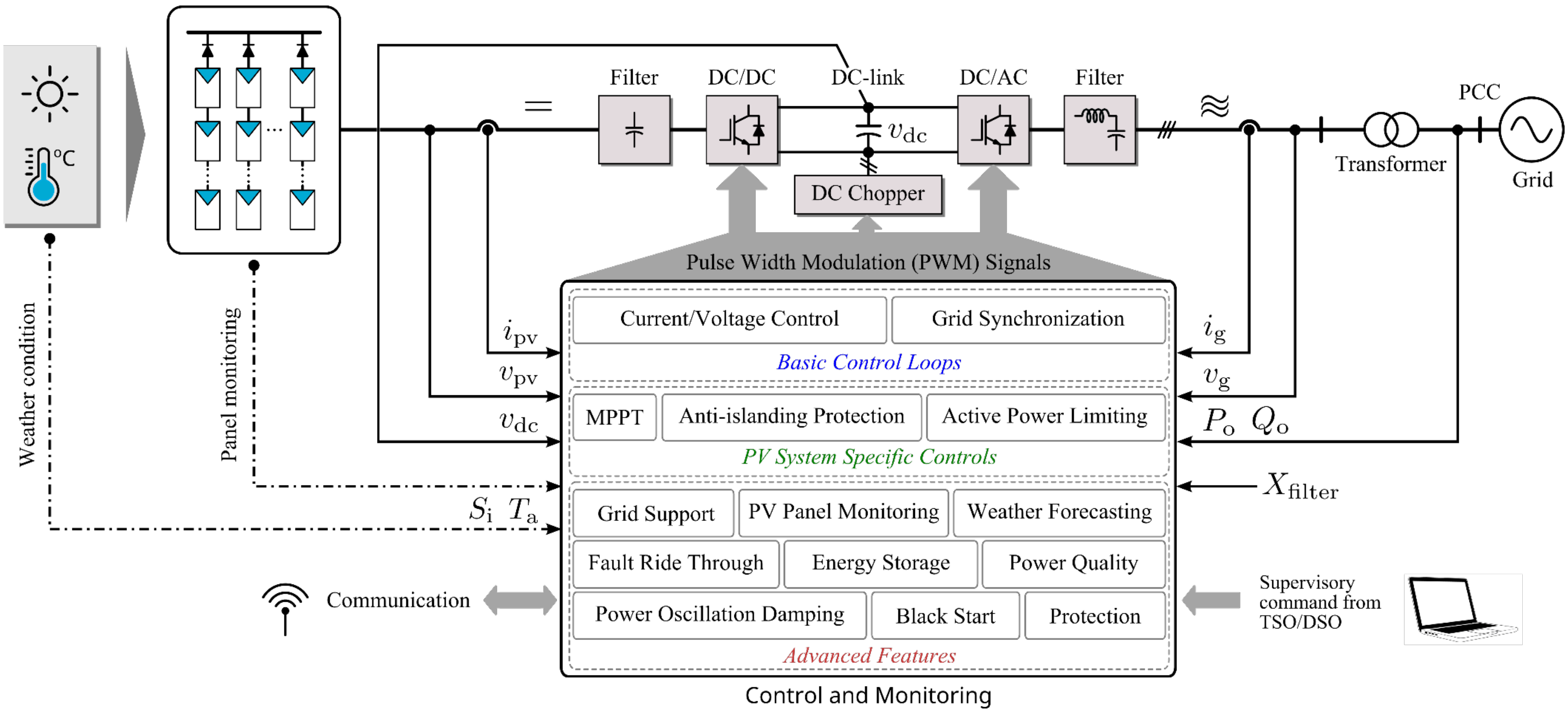
Active/Reactive Power Regulation in Wind Farm



- ❖ Advanced grid support feature achieved by power converters and controls
- ❖ Local/Central storage system by batteries/supercapacitors
- ❖ Reactive power compensators
  - STATCOMs/SVCs
  - Medium-voltage distribution grid/High-voltage transmission grid

Control for renewable energy systems

General Control Structure for PV Systems



Basic functions – all grid-tied inverters

- Grid current control
- DC voltage control
- Grid synchronization

PV specific functions – common for PV inverters

- Maximum power point tracking – MPPT
- Anti-Islanding (VDE0126, IEEE1574, etc.)
- Grid monitoring
- Plant monitoring
- Sun tracking (mechanical MPPT)

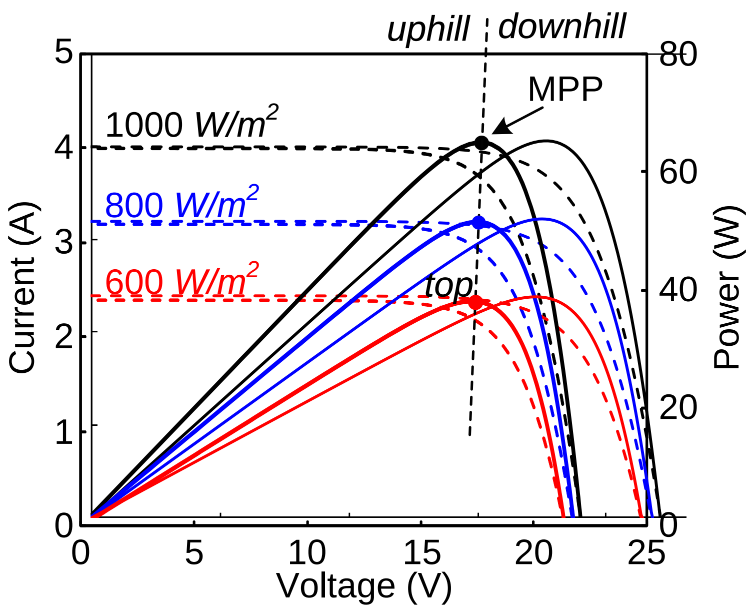
Ancillary support – in effectiveness

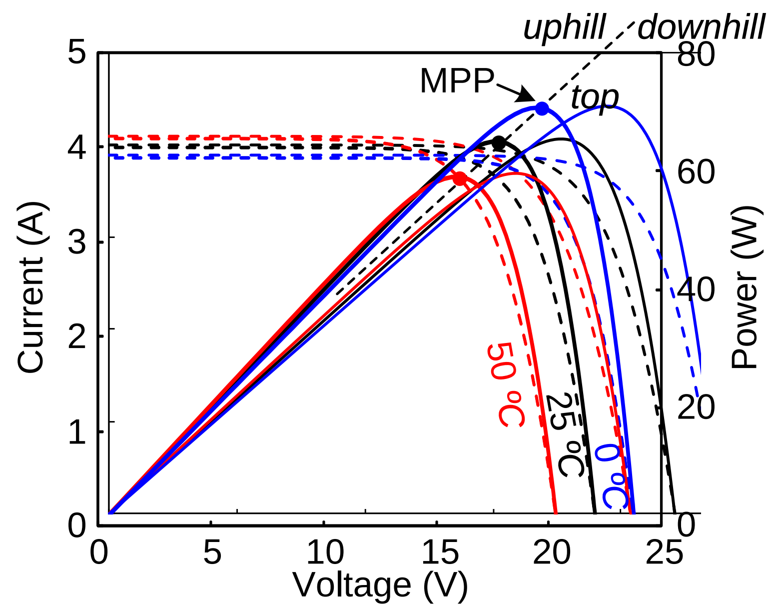
- Voltage control
- Fault ride-through
- Power quality
- …

Maximum Power Point Tracking (MPPT)

Role of MPPT - namely to maximize the energy harvesting

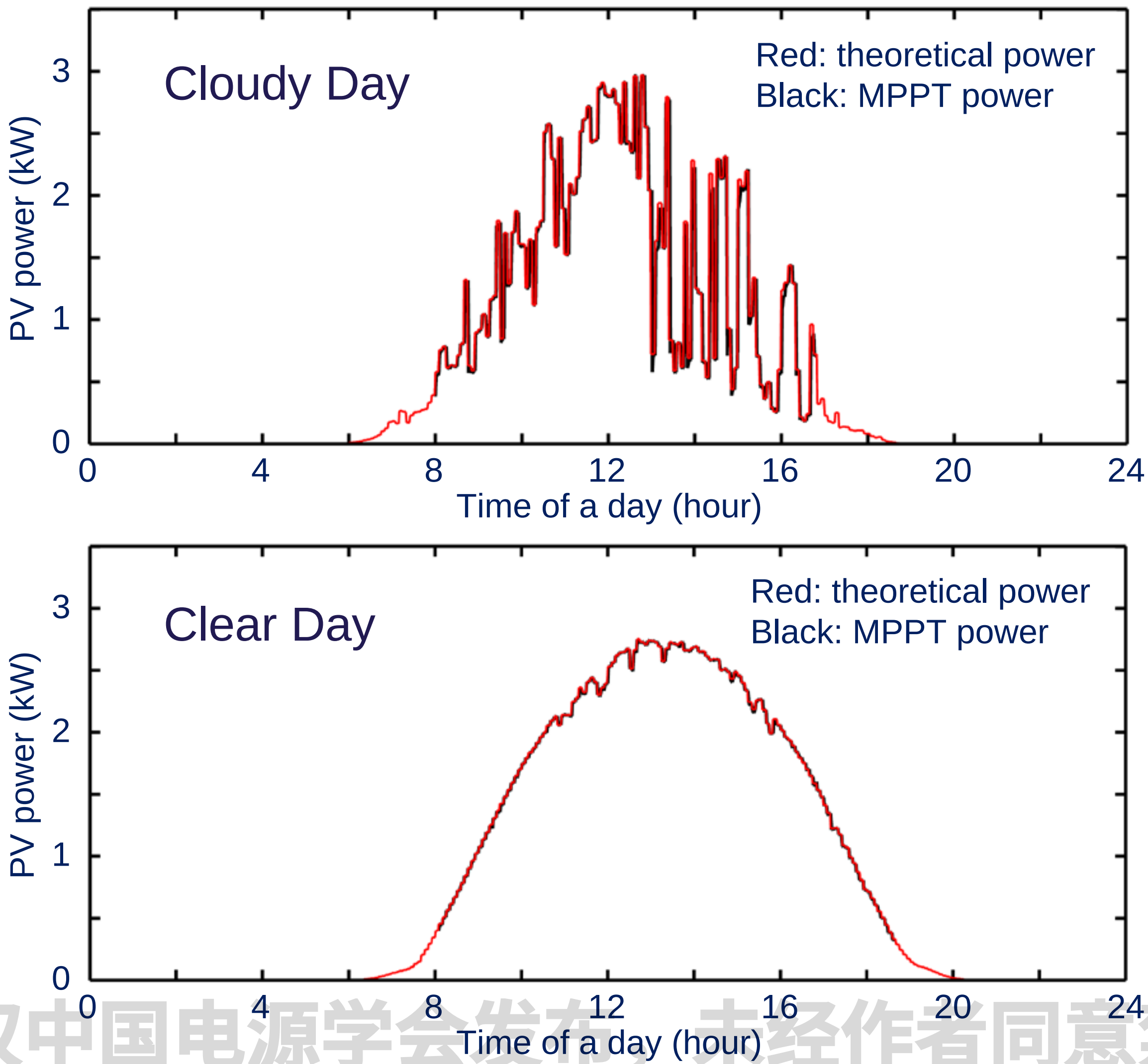
- PV array characteristic is non-linear → Maximum Power Point (MPP)
- MPP is weather-dependent → Maximum Power Point Tracking (MPPT)





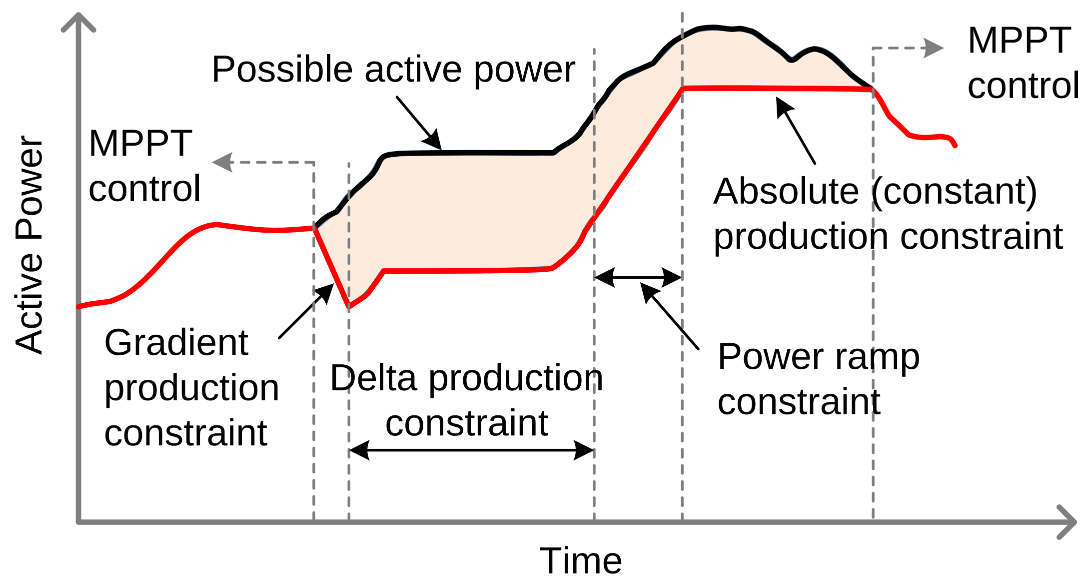
Example of MPPT Control

Experiments of P&O on a 3-kW double-stage system:



Constant Power Generation (CPG) Concept

CPG – one of the Active Power Control (APC) functions

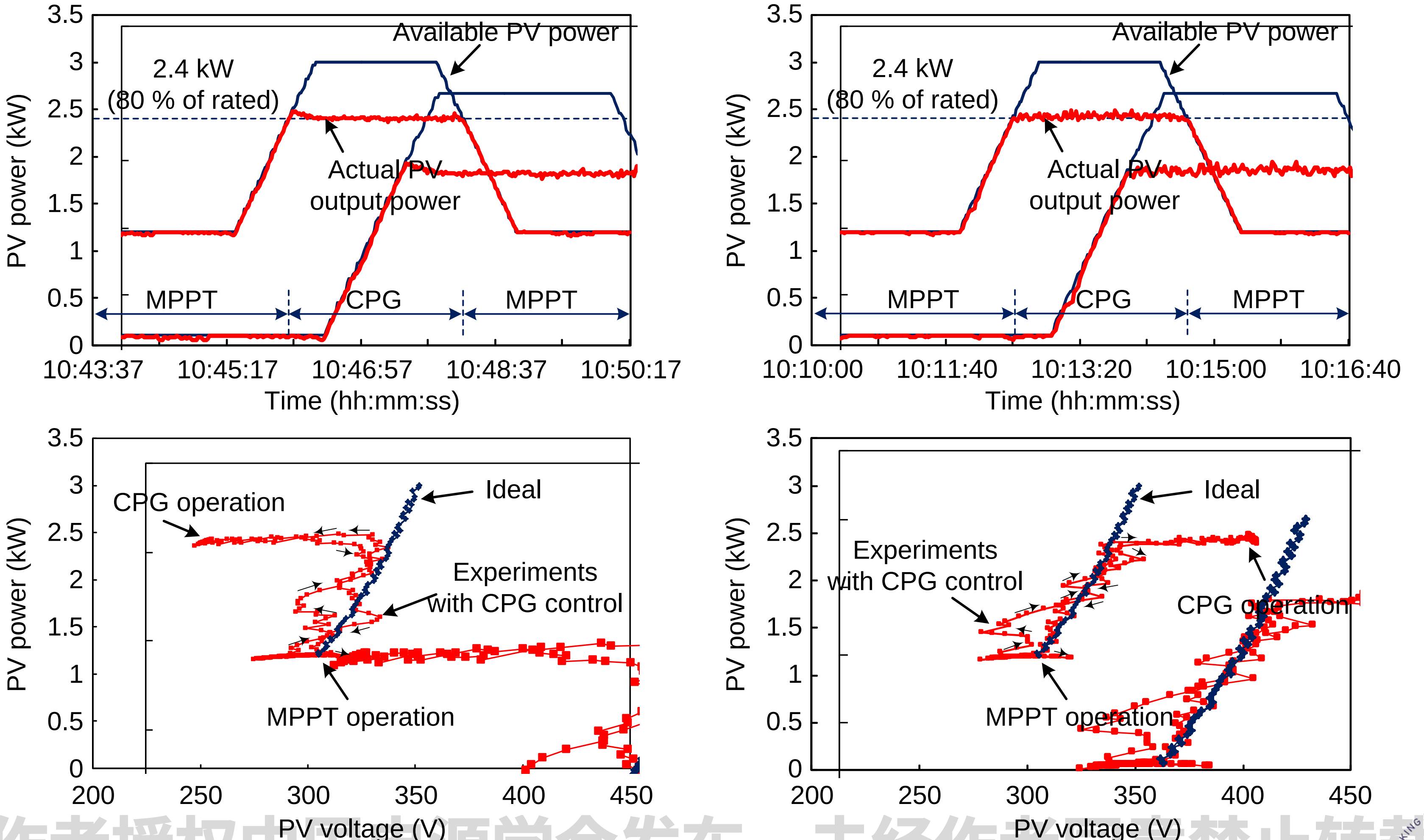


Extend the CPG function for WTS in Denmark to wide-scale PV applications?

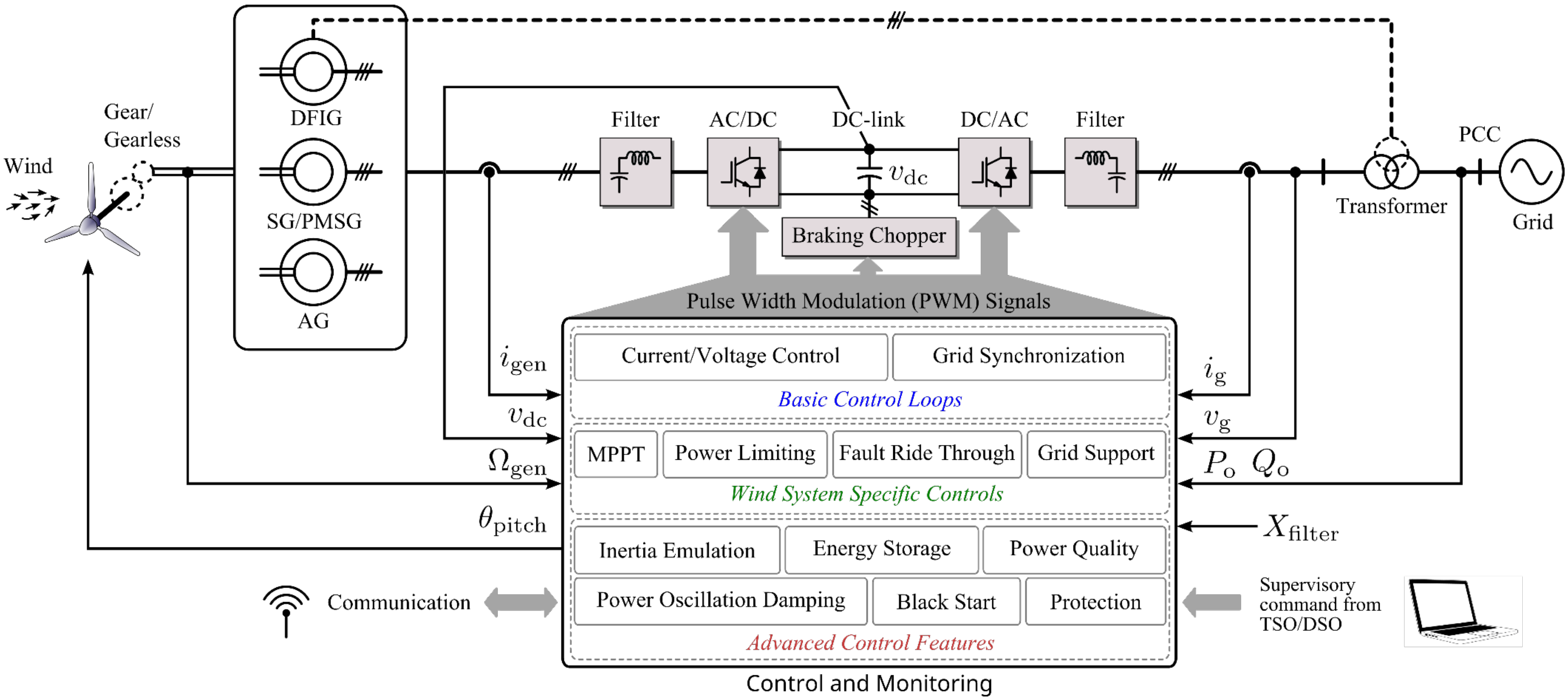
Y. Yang, F. Blaabjerg, and H. Wang, "Constant power generation of photovoltaic systems considering the distributed grid capacity," in *Proc. of APEC*, pp. 379-385, 16-20 Mar. 2014.

Constant Power Generation (CPG) Concept

Operation examples of CPG control (experiments)



General Control structure for Wind Turbine System



Level I – Power converter

- ✓ Grid synchronization
- ✓ Converter current control
- ✓ DC voltage control

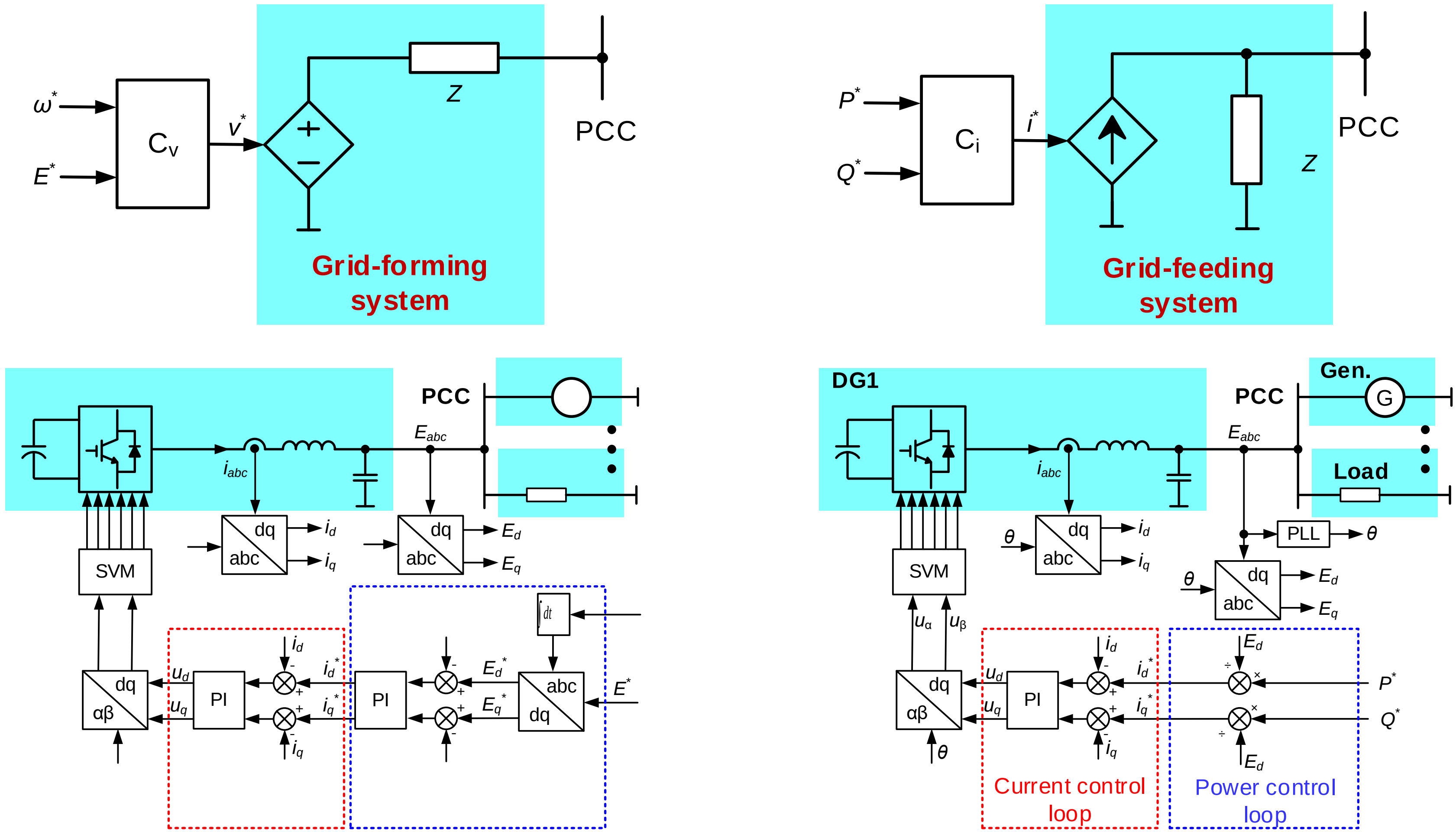
Level II – Wind turbine

- ✓ MPPT
- ✓ Turbine pitch control
- ✓ DC Chopper

Level III – Grid integration

- ✓ Voltage regulation
- ✓ Frequency regulation
- ✓ Power quality

Grid-forming & Grid-feeding Systems (examples)



- Voltage-source based inverter
- Control reference: voltage amp. & freq.

- Current-source based inverter
- Control reference: active & reactive power

Summary

Summary of presentation

- Solar power fully competitive with fossil today
- Large pressure on reducing CoE for wind
- WBG might reduce converter technology size and cost !?
- All types of PV inverters will evolve – but not major cost in PV..
- Grid codes will constant change
- More intelligence into the control of renewables
- Grid-feeding/Grid forming – how to do in large scale systems ?
- Storage is coming into system solutions – be more and more used
- Other energy carriers will be a part of large scale system balance
- Renewables 100 % competitive in 10 Years………. Power electronics is enabling the technology

Acknowledgment

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from Department of Energy Technology
Aalborg University

Look at

www.et.aau.dk
www.corpe.et.aau.dk
www.harmony.et.aau.dk

Thank you for your attention!

Aalborg University
Department of Energy Technology
Aalborg, Denmark

AALBORG UNIVERSITY
DENMARK

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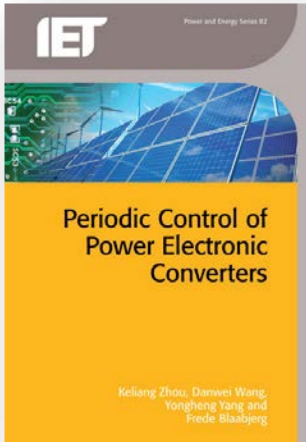

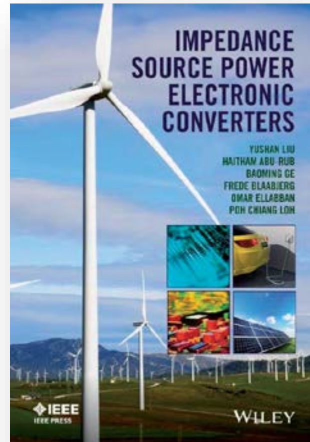

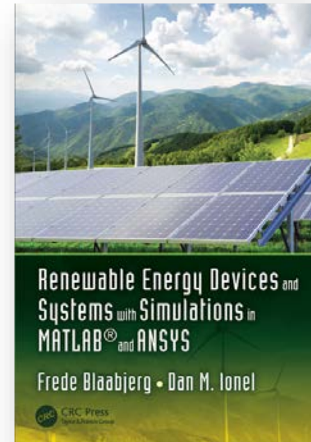

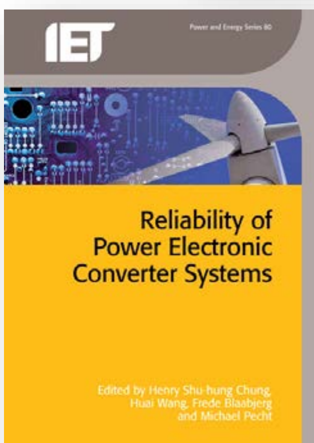

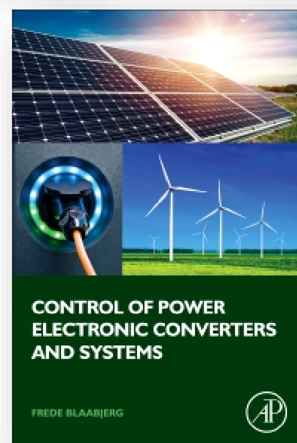

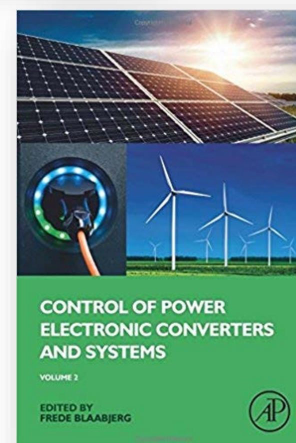

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