Power Electronics - Key Technology for Renewable Energy Systems

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Outline

Power Electronics -
Key Technology for Renewable Energy Systems –
Status and future

- Aalborg University, Department of Energy Technology, Denmark
- Renewable Energy in Denmark
- Power Electronics for Wind Turbines
- Power Electronics for Photovoltaics
- Challenges of Power Electronics in Renewable Energy Systems
- Conclusions

Aalborg University
Department of Energy Technology, Denmark

Aalborg University - Denmark

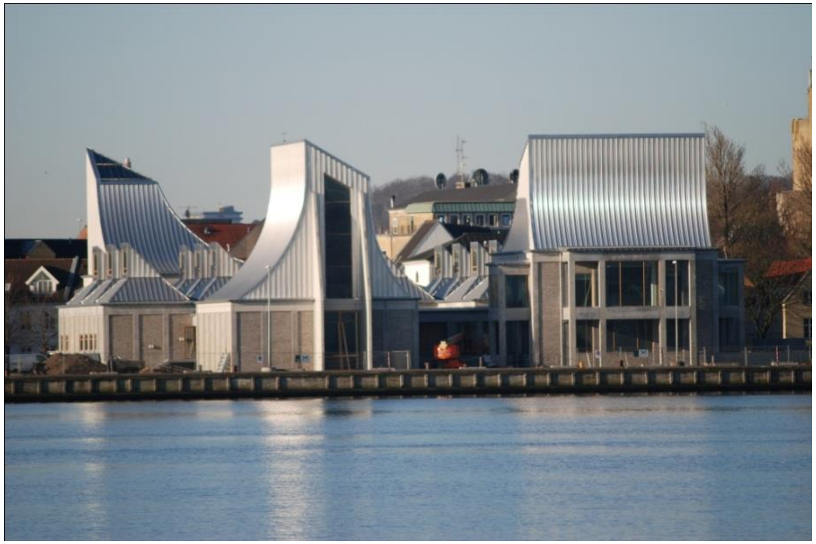
Inaugurated in 1974
20,000 students
2,00 faculty

BREAKING NEW GROUND
AALBORG UNIVERSITY

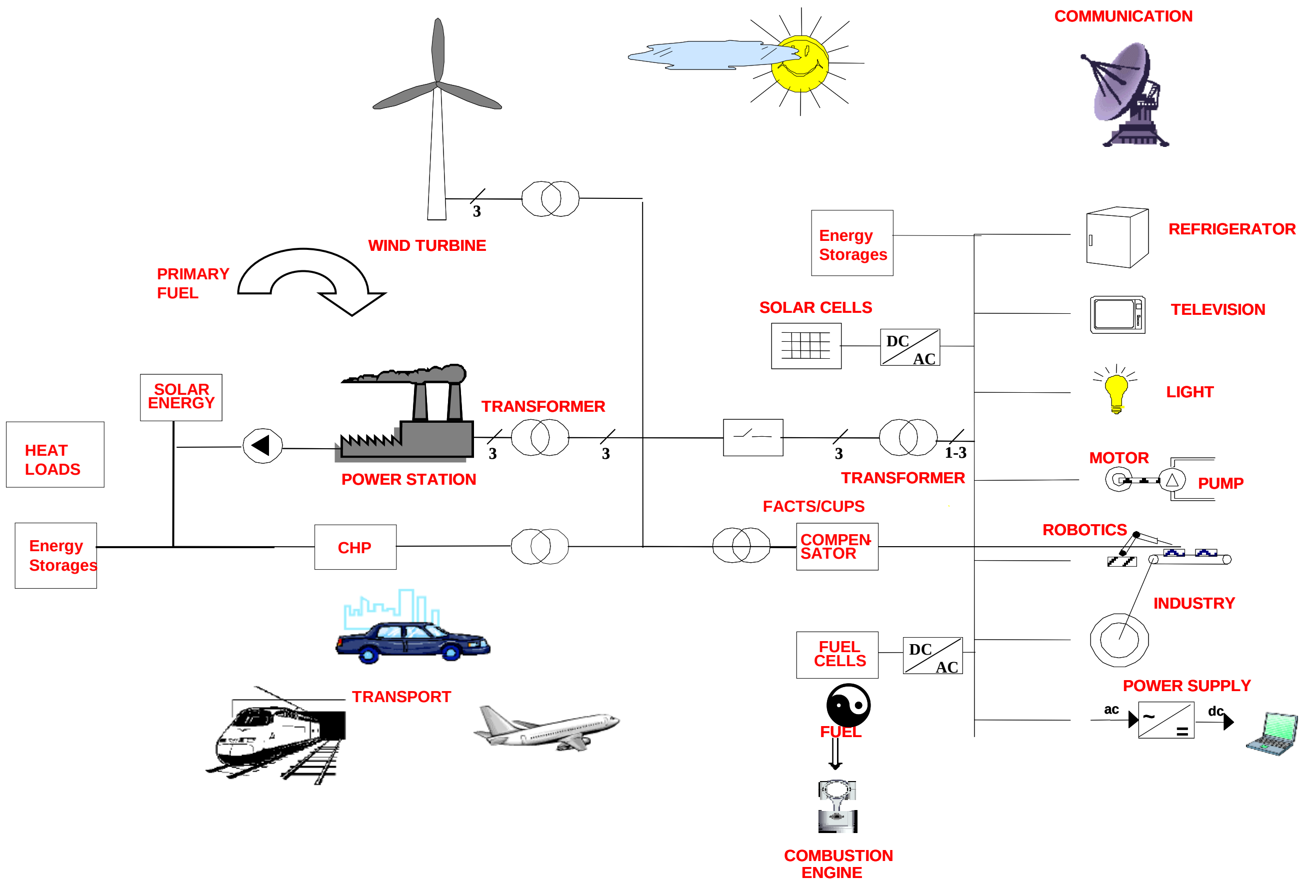
PBL-Aalborg Model

(Project-organised and problem-based)

Aalborg University - Campus



Department of Energy Technology



Energy production - distribution - consumption - control

Department of Energy Technology

Department of Energy Technology

- Electric Power Systems
- Power Electronic Systems
- Electrical Machines
- Fluid Power and Mechatronic Systems
- Fluid Mechanics and Combustion
- Thermal Energy Systems

Strategic Networks

- EMSD
- CEES
- ECPE
- VE-NET
- DUWET
- WEST
- VPP
- REN-DK
- HUB NORTH
- Energy Sponsor Programme

- 50+ VIP
- 70+ PhD
- 10+ Guest Researchers
- 10+ Research Assistants
- 22 TAP

Multi-disciplinary Research Programmes

- Wind Turbine Systems
- Fluid Power in Wind and Wave Energy
- Biomass
- Photovoltaic Systems and Microgrids
- Modern Power Transmission Systems
- Smart Grids and Active Networks
- Fuel Cell and Battery Systems
- Automotive and Industrial Drives
- Efficient and Reliable Power Electronics
- Thermoelectrics
- Green Buildings

Lab. Facilities

- Power Electronics Systems
- Drive Systems Tests
- Fluid Power
- Power Systems & RTDS
- Micro Grid
- High Voltage
- dSPACE
- PV Converter & Systems
- Laser Systems
- Fuel Cell Systems
- Battery Test
- EMC
- Vehicles Test Lab
- Biomass Conversion Facilities
- Proto Type Facilities

Renewable Energy in Denmark

Energy and Power Challenge

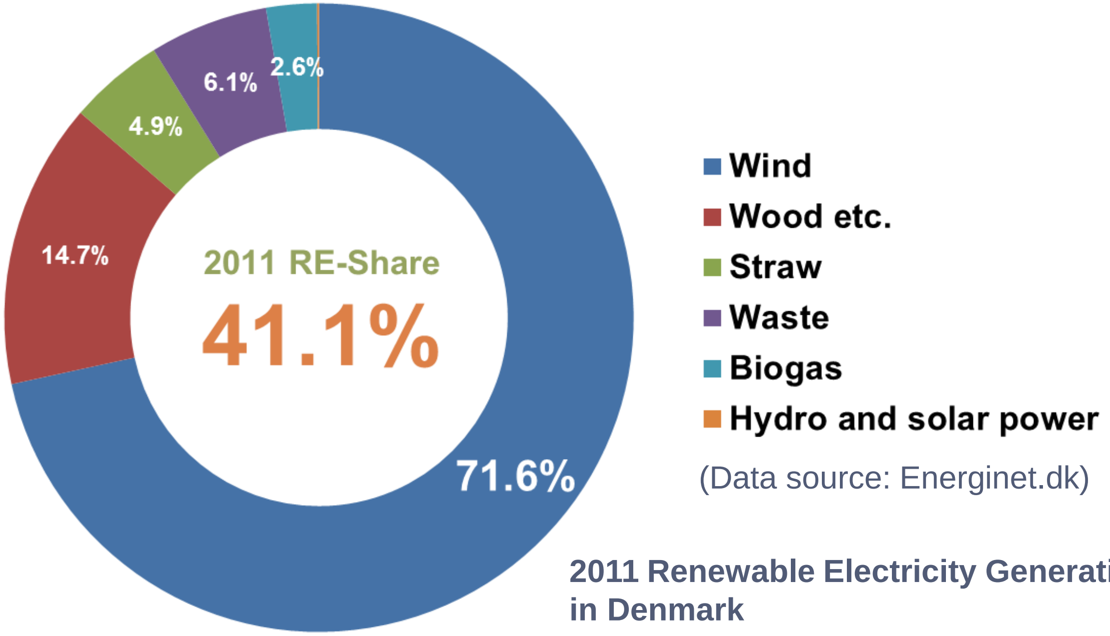
Four main challenges in energy

Sustainable energy production (backbone, weather based, storage)
Energy efficiency
Mobility
Infrastructure

Different initiatives

EU Set-plan (20-20-20) and beyond
Danish Climate Commision – Independent in 2050
Germany – no nuclear in the future (2022)
Globally large activity

Renewable Electricity in Denmark

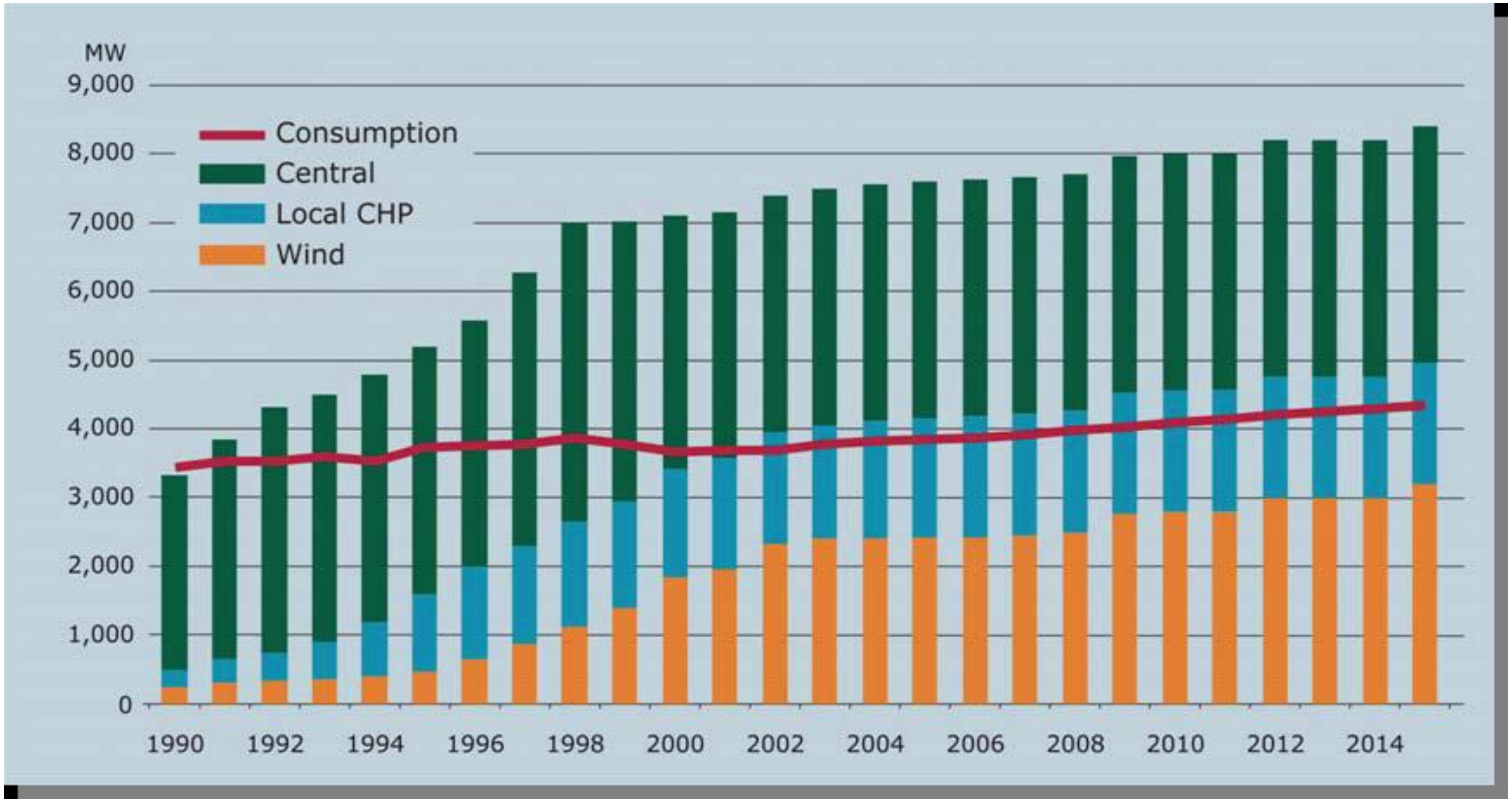


2011 Renewable Electricity Generation in Denmark

Key figures for proportion of renewable electricity (Data source: Energinet.dk) (*target value)

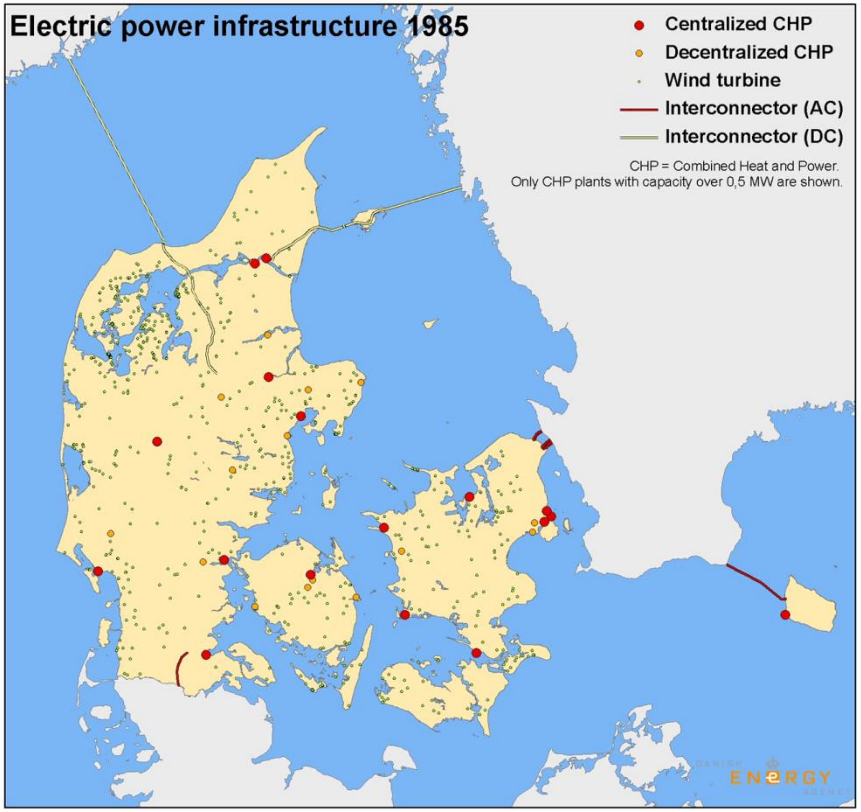
Key figures	2010	2011	2020	2035
Wind share of net generation in year	21.3%	29.4%	50%*	
Wind share of consumption in year	22.0%	28.3%		
RE share of net generation in year	32.8%	41.1%		100%*
RE share of net consumption in year	33.8%	39.0%		

Energy and Power Challenge in DK

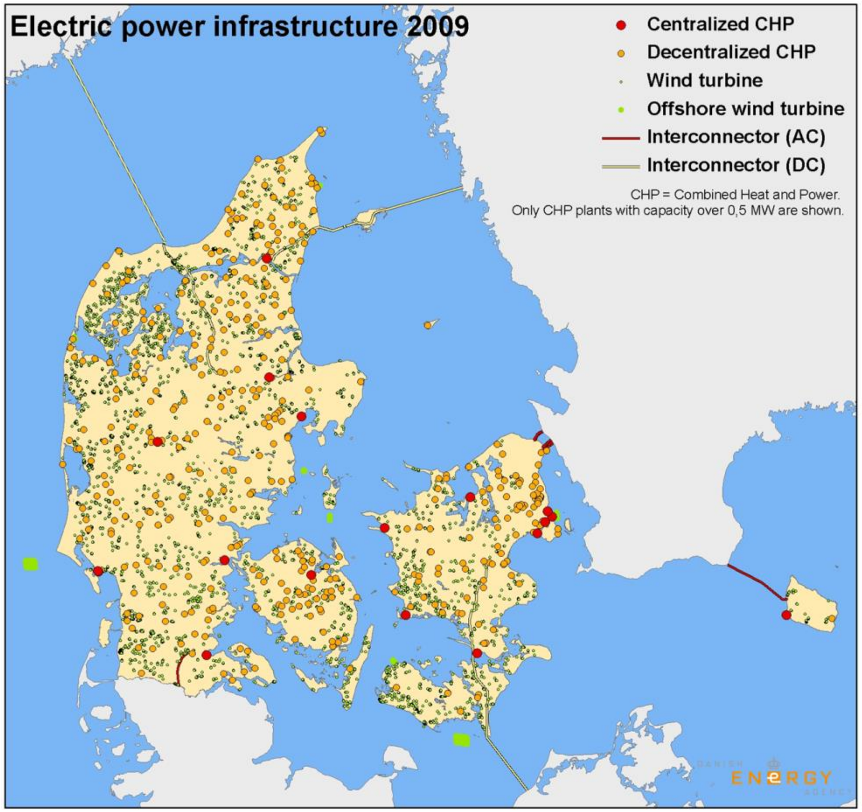


Very high coverage of distributed generation.

Development of Electric Power System in Denmark



(Picture Source: Danish Energy Agency)

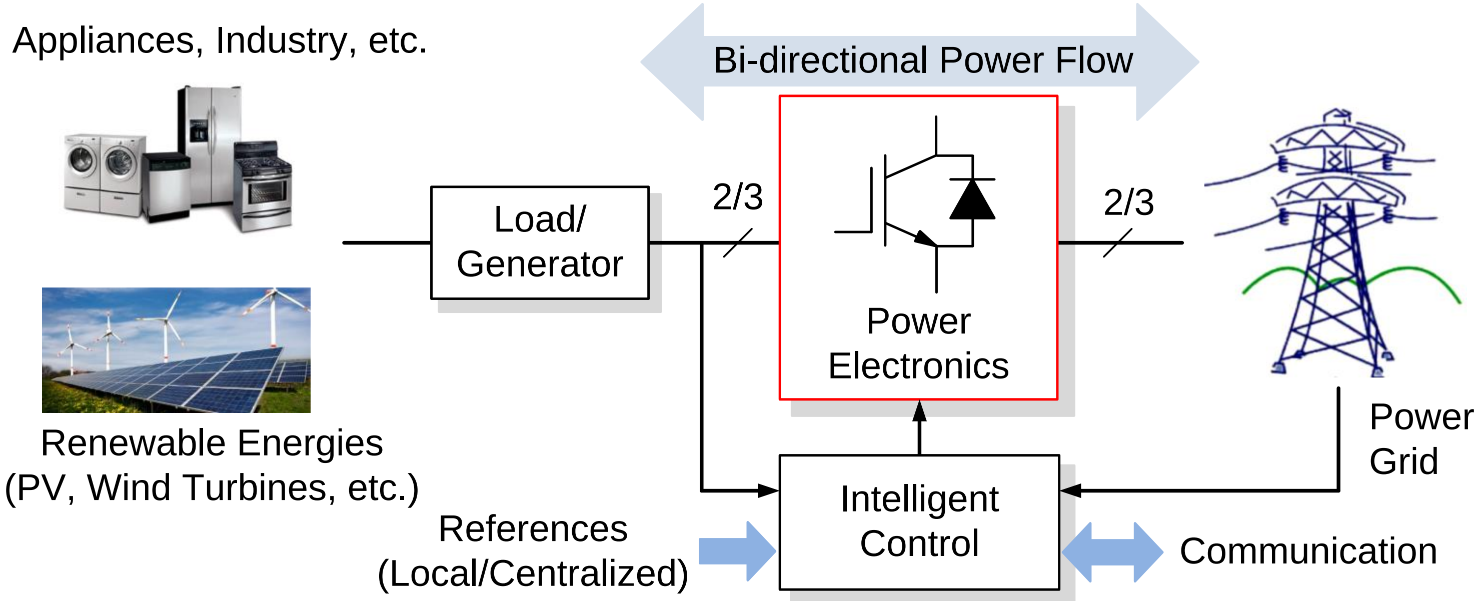


(Picture Source: Danish Energy Agency)

From Central to De-central Power Generation

Power Electronics for Wind Turbines

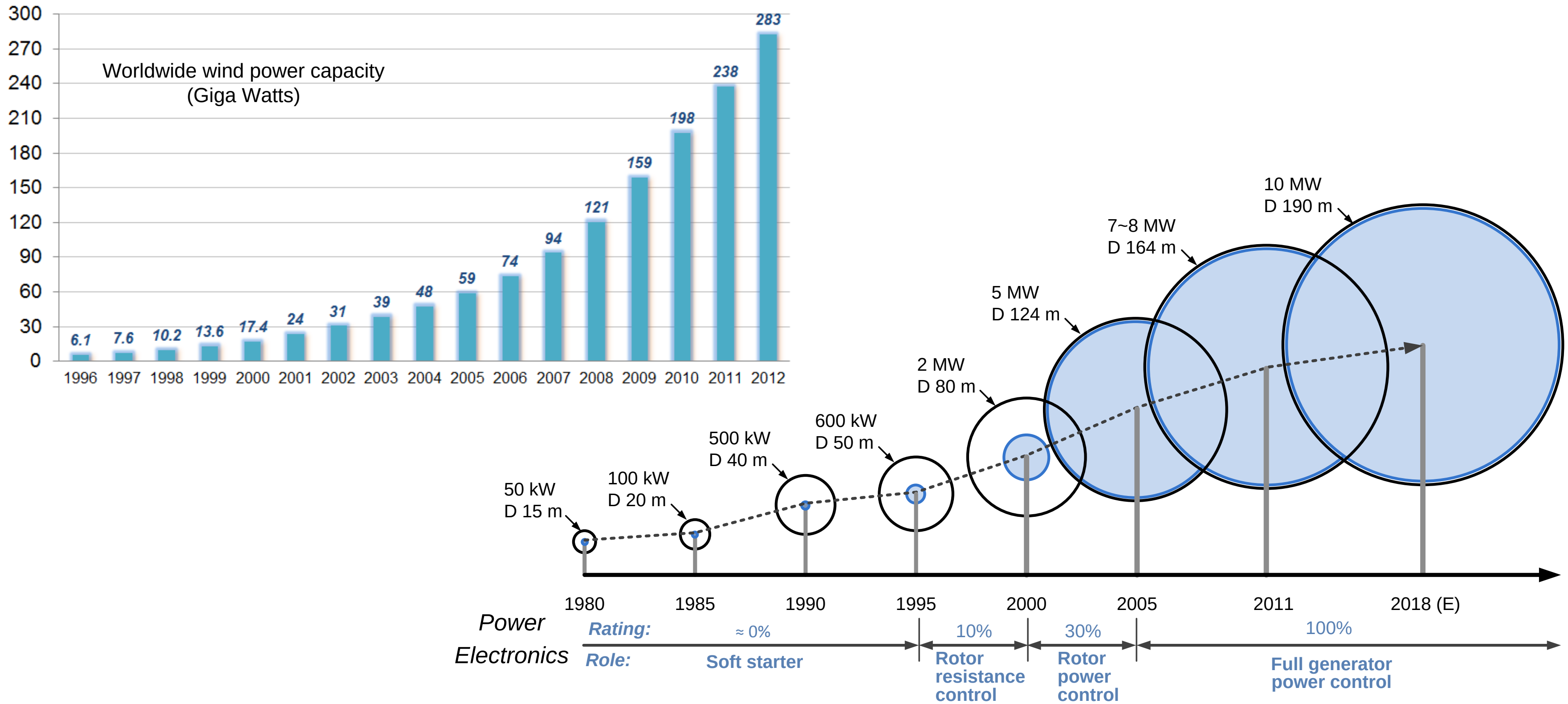
Renewable Energy System



Important issues for power converters

Reliability/security of supply
Efficiency, cost, volume, protection
Control active and reactive power
Ride-through operation and monitoring
Power electronics enabling technology

Wind Turbine Development



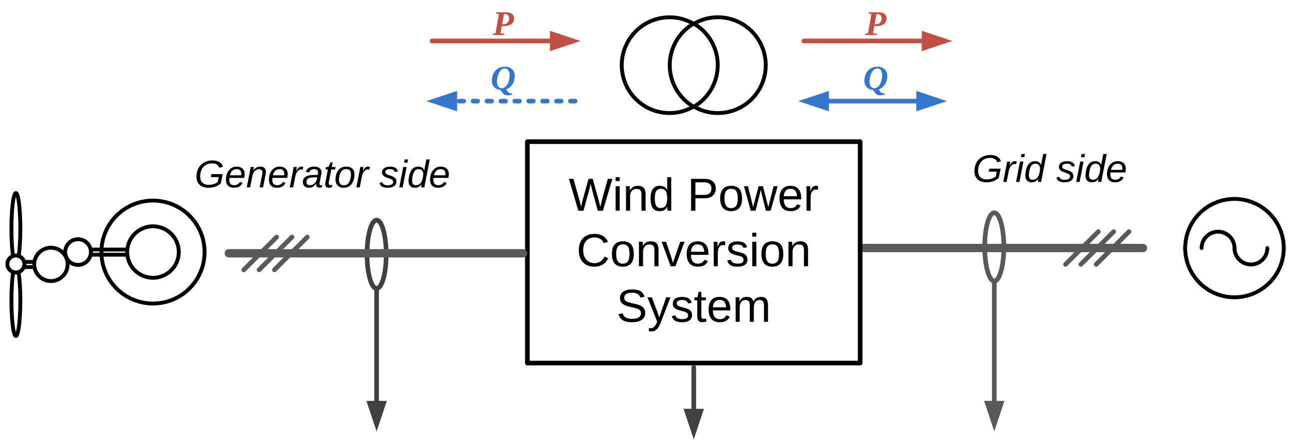
Global installed wind capacity (up to 2012): 283 GW, 2012: 45 GW

Higher total capacity (59 % non-hydro renewables).

Larger individual size (average 1.8 MW, up to 8 MW).

More power electronics (up to 100 % rating coverage).

Requirements for Wind Turbine Systems



Generator side:

1. Controllable *I*
2. Variable *freq* & *U*

Wind Power Conversion System:

1. Energy balance/storage
2. High power density
3. Strong cooling
4. Reliable

Grid side:

1. Fast/long *P* response
2. Controllable/large *Q*
3. *freq* & *U* stabilization
4. Low Voltage Ride Through

General Requirements & Specific Requirements

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.

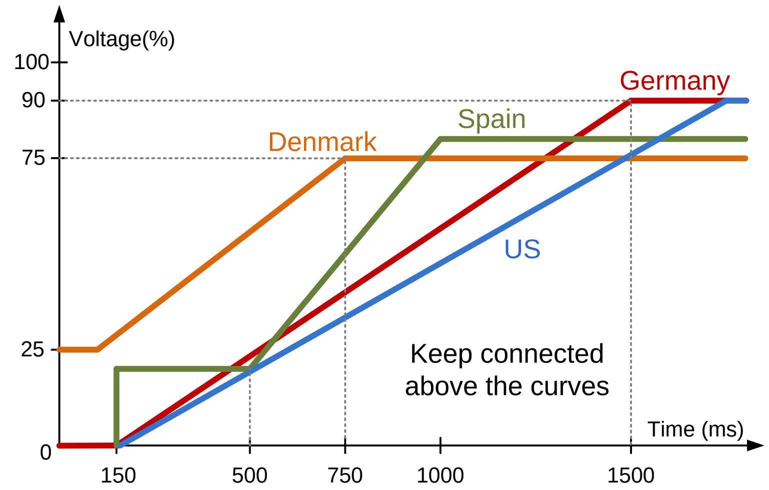
Wind turbine technology differs from conventional power plants regarding the converter-based grid interface and asynchronous operation

Grid code requirements today

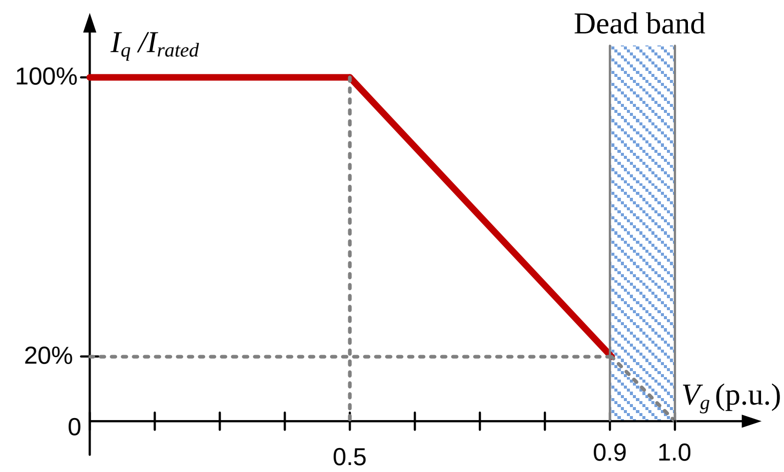
- Active power control
- Reactive power control
- Frequency control
- Steady-state operating range
- Fault ride-through capability

Wind turbines are active power plants.

Requirements during grid faults



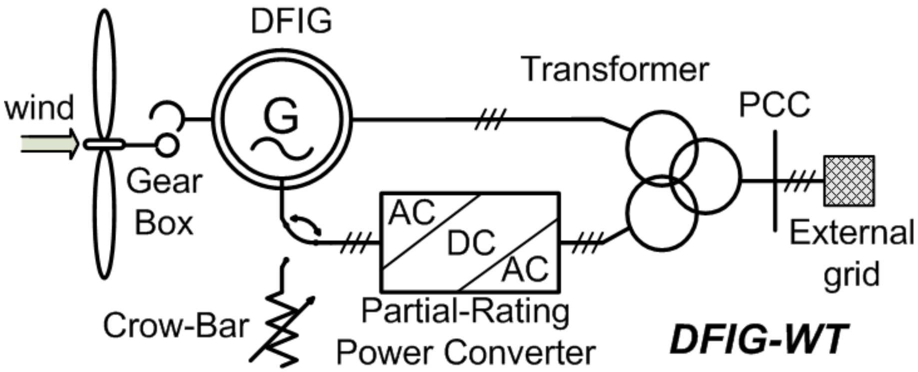
Grid voltage dips vs. withstand time



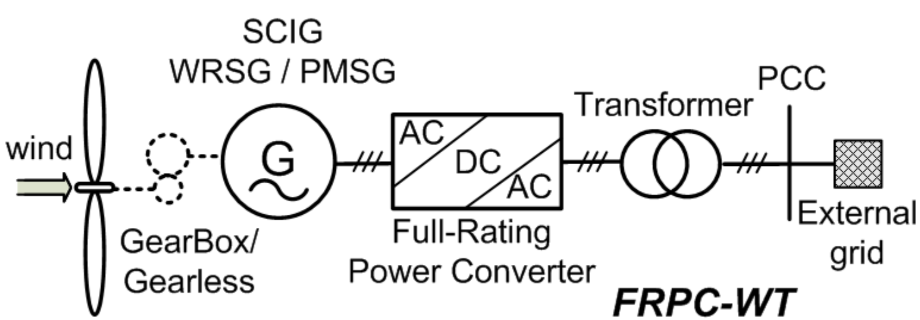
Reactive current vs. Grid voltage dips

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

Wind Turbine Concepts



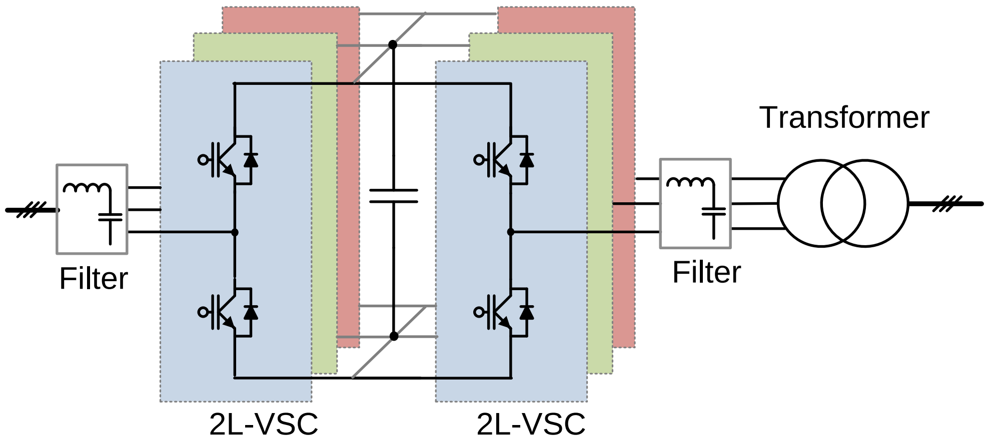
- **Wound-rotor induction generator**
- **Variable pitch – variable speed**
- **±30% slip variation around synchronous speed**
- **Power converter** (back to back/ direct AC/AC) **in rotor circuit**



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

Power Electronic Converters

Back-to-back VSC



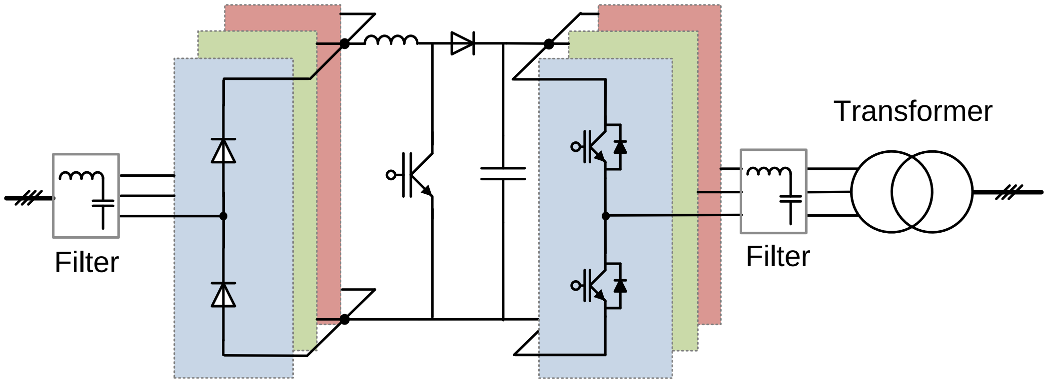
Back-to-back two-level voltage source converter

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

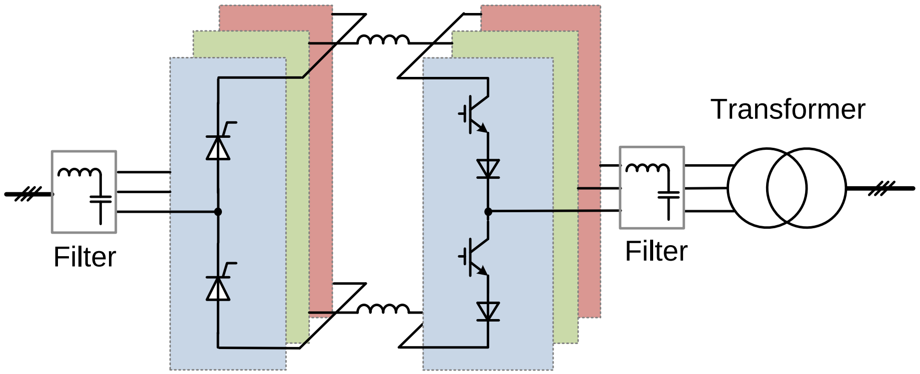
- **Need for major energy-storage in DC-link (reduced life-time and increased expenses)**
- **Power losses (switching and conduction losses)**

Power Electronic Converters

Boost and Voltage Source Converter to grid



Current Source Inverter to grid

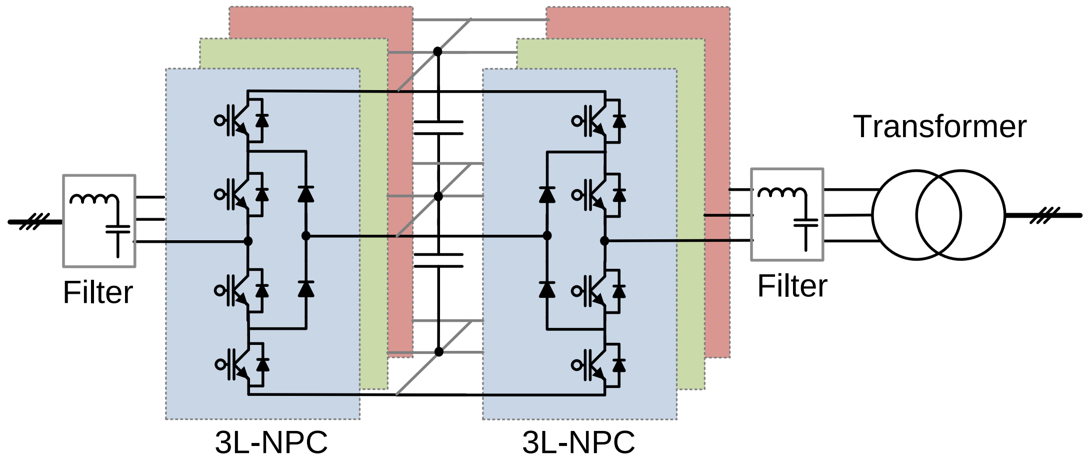


Power converters

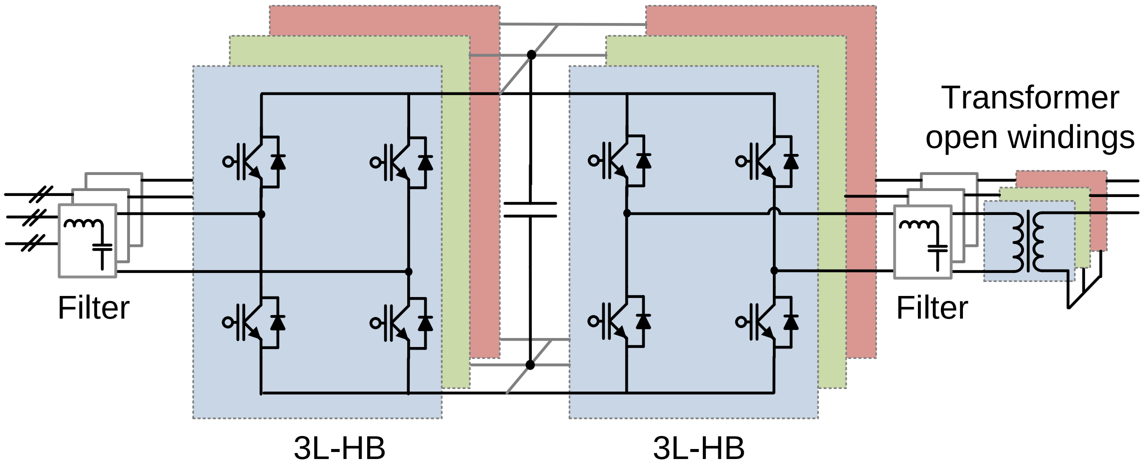
- **Proven technologies today**

Multi-Level Topologies +6 MW

Three-level NPC

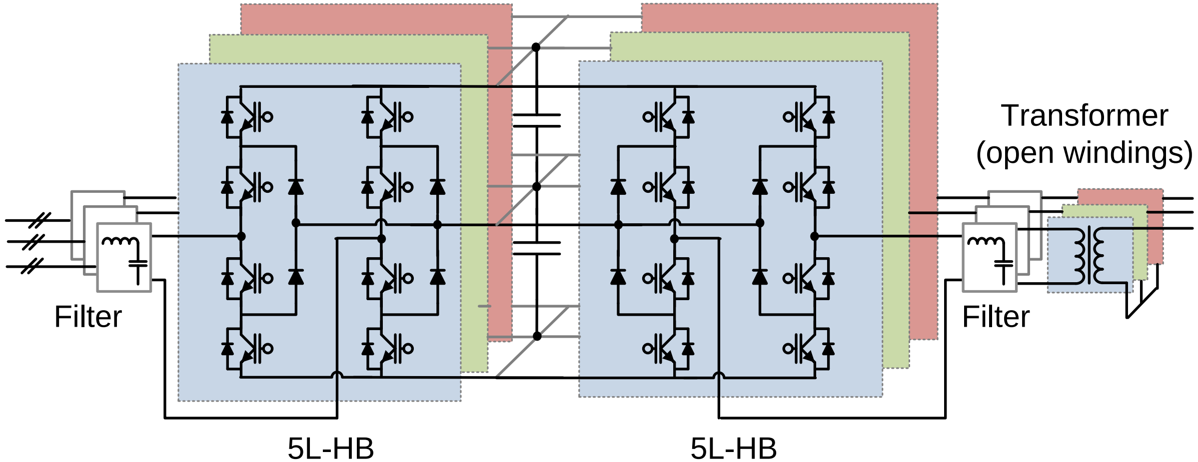


Half-bridge and open-winded transformer

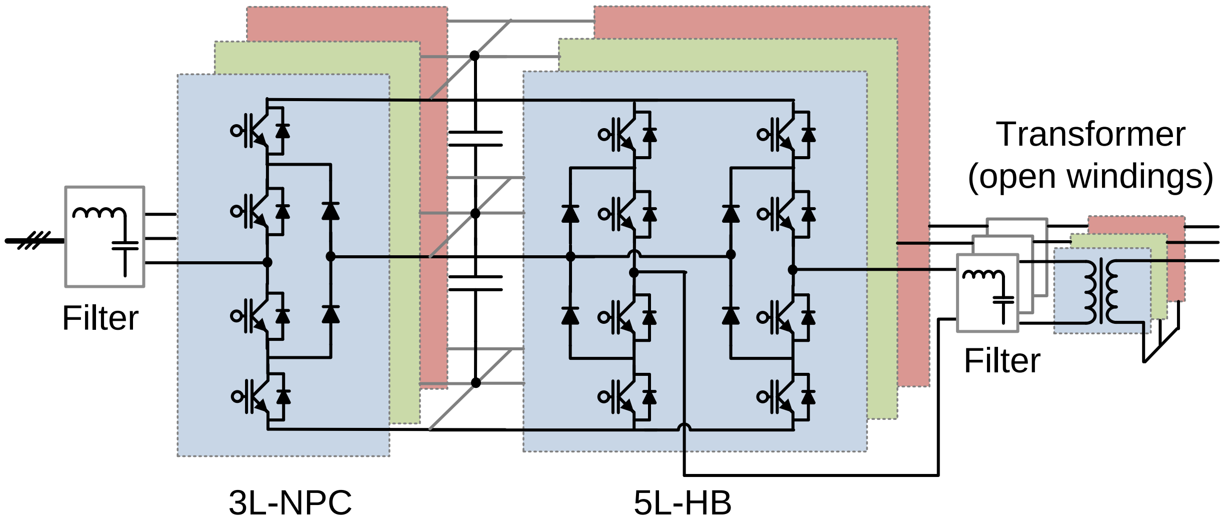


Multi-Level Topologies +6 MW

Half-bridge, five-level

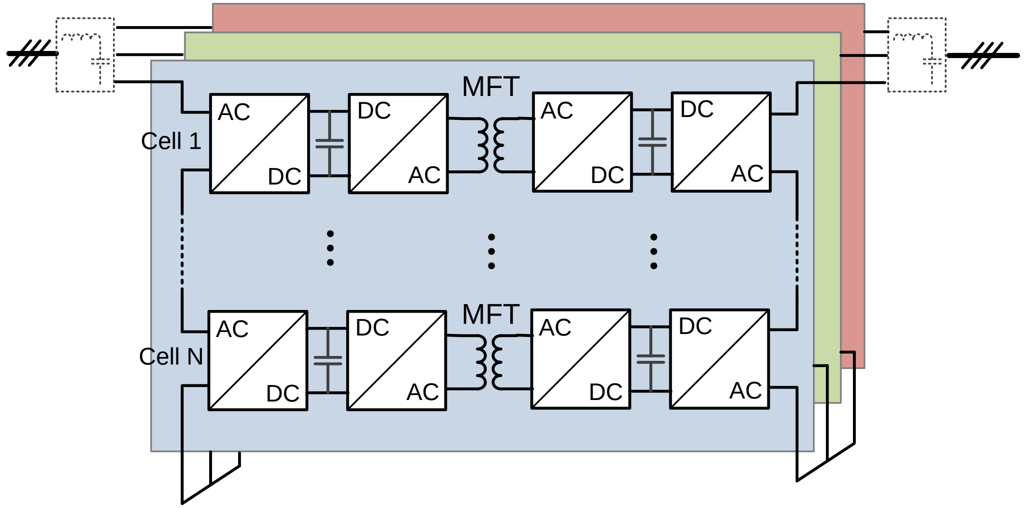


Three-level and five-level

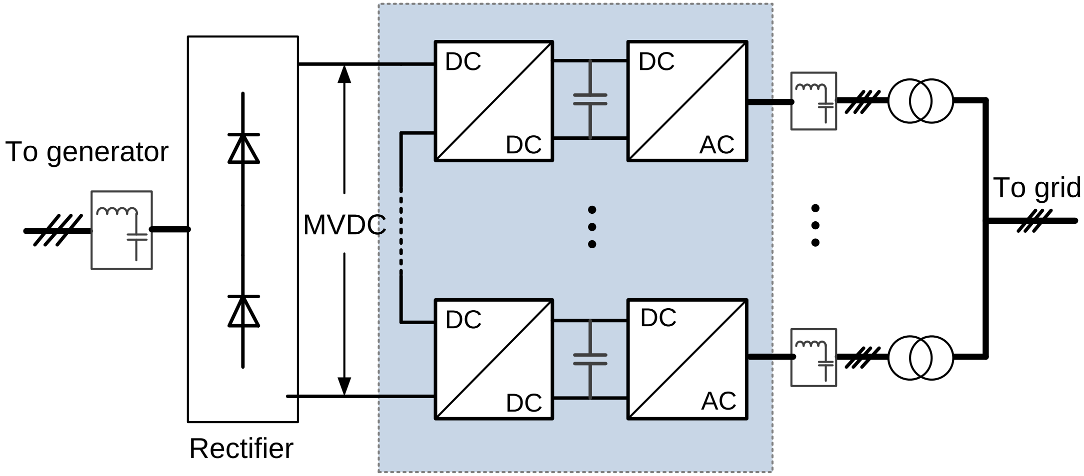


Multi-Level Topologies +6 MW

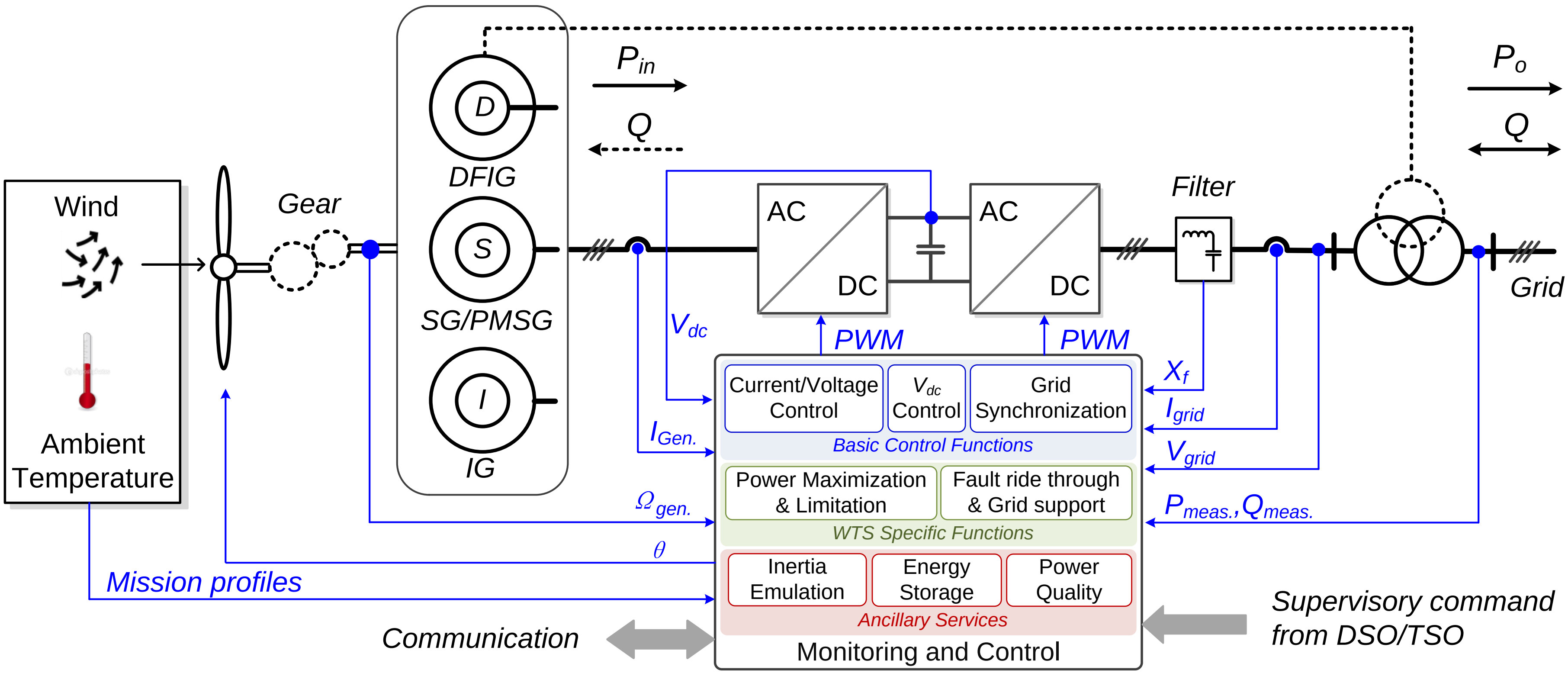
Medium frequency transformer



Stacked output converter



Control Structure for a Wind Turbine System



Power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power.

Current Development Example

Vestas Wind Systems A/S Denmark

Target market: Big offshore farms

Vestas V164 offshore turbine

Rated power: 8,000 kW

Rotor diameter: 164 m

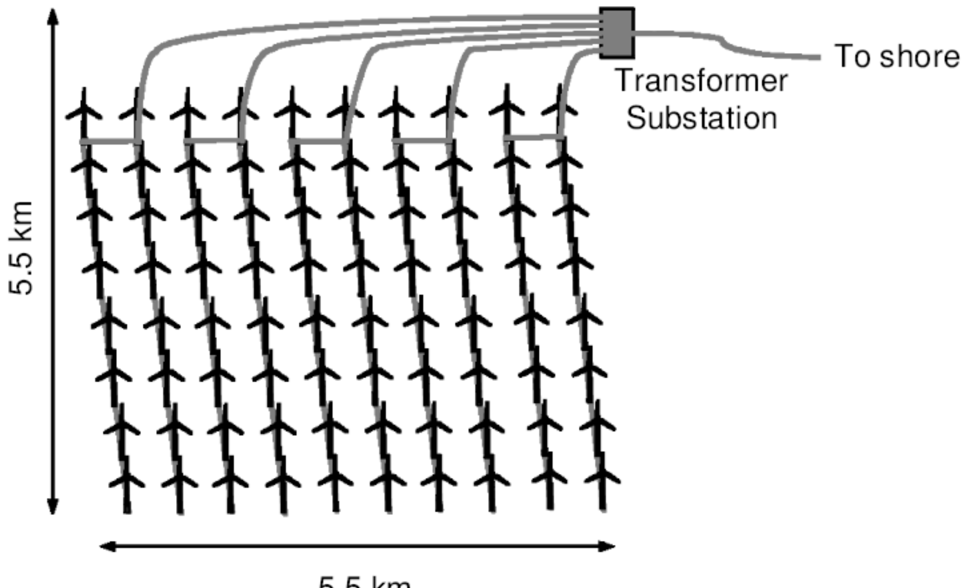
Hub height: min. 105 m

Turbine concept: medium-speed gearbox, variable speed, variable pitch, full-scale power converter

Generator: permanent magnet

Current Development Example – Wind Farm

Horns Reef I 160 MW, Horns Reef II 209.3 MW

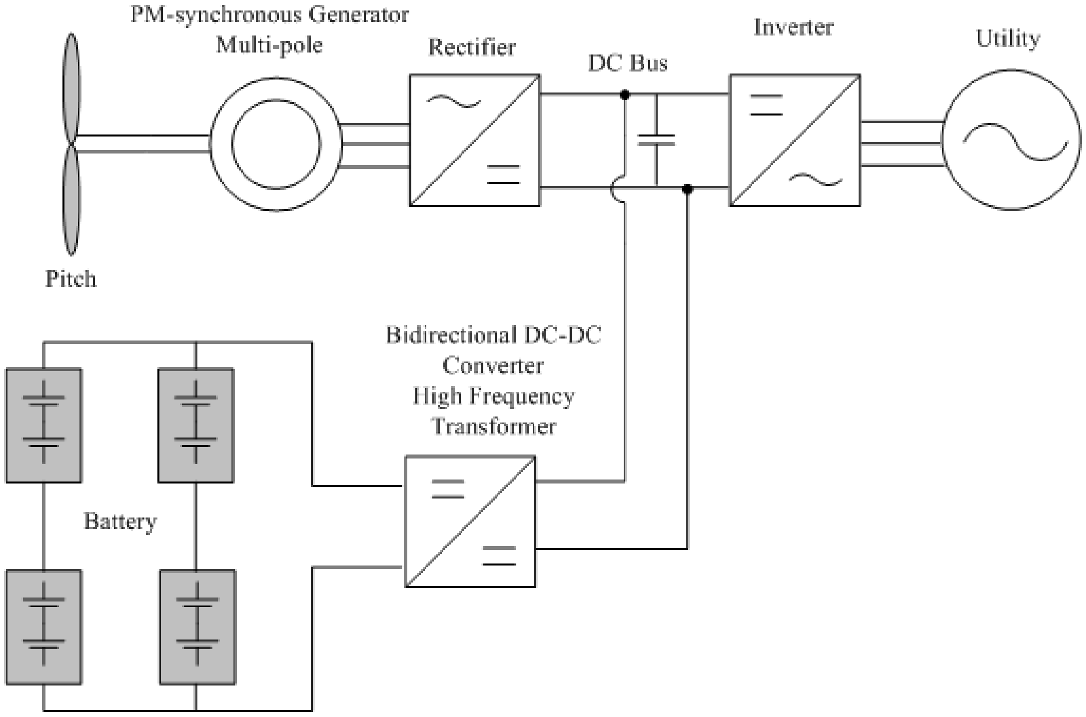


- **80 x 2MW (Vestas V80, in operation Dec 11, 2002)**
- **91 x 2.3MW (Siemens SWT-2.3-93, in operation Sep 17, 2009)**

Vestas V80–2.0 MW

Rotor Diameter	**80 m**
Hub Height	**60-100 m**
Weight	**227-303 tons**
Min/Max rotation speed	**9/19 rounds/minute**
Min/Nom/Max Wind	**4/16/25 m/s**
Gear box	**Yes (1:100.5)**
Generator	**DFIG (4 pole – slip rings)**

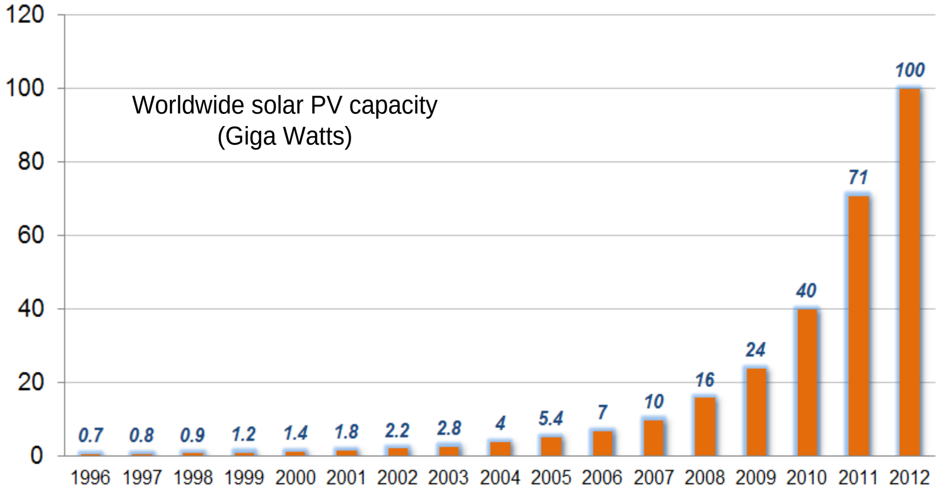
Improved Performance of Wind Turbines

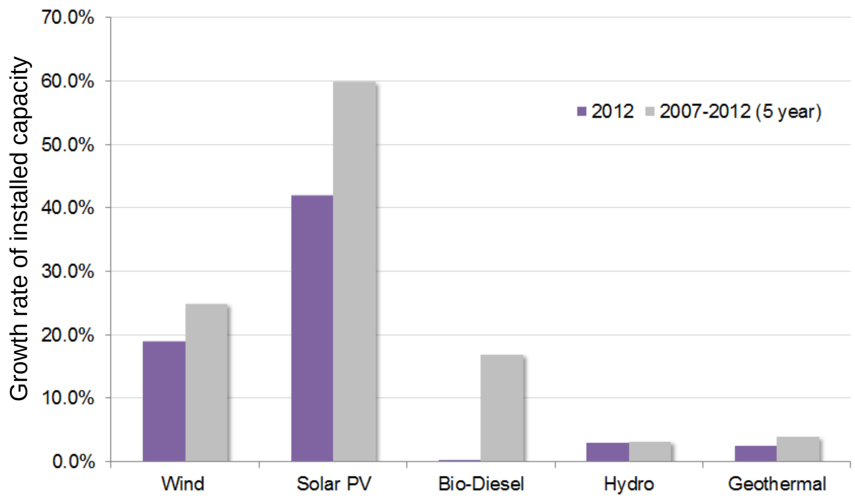


Variable speed wind turbine integrated with a battery storage system

Power Electronics for Photovoltaics

Photovoltaic System Development

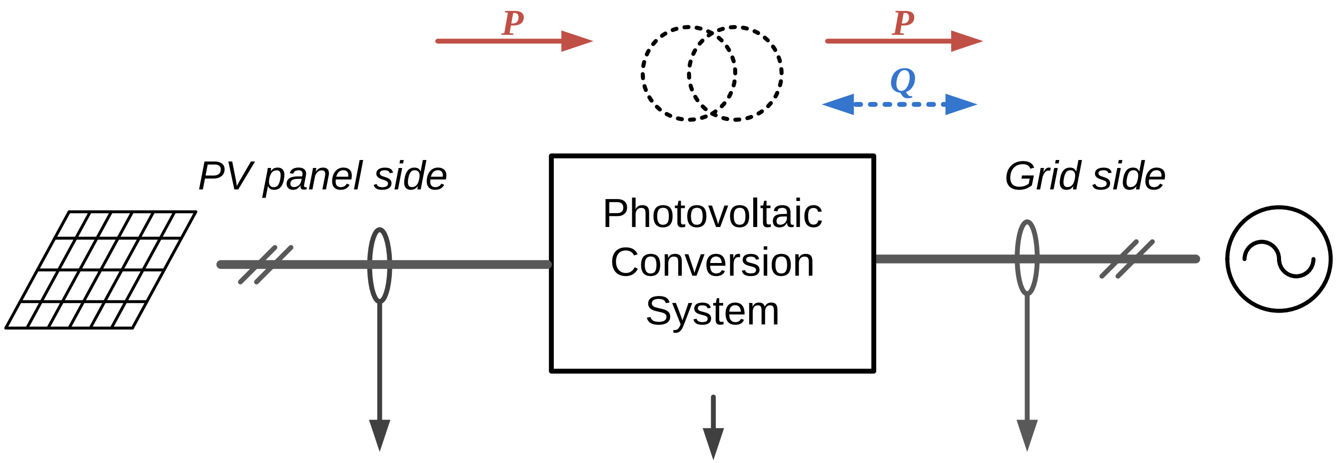




Global installed PV capacity (up to 2012): 100 GW, 2012: 29 GW

More significant total capacity (21 % non-hydro renewables).
Fast growth rate (60 % between 2007-2012).

Requirements for Photovoltaic Systems



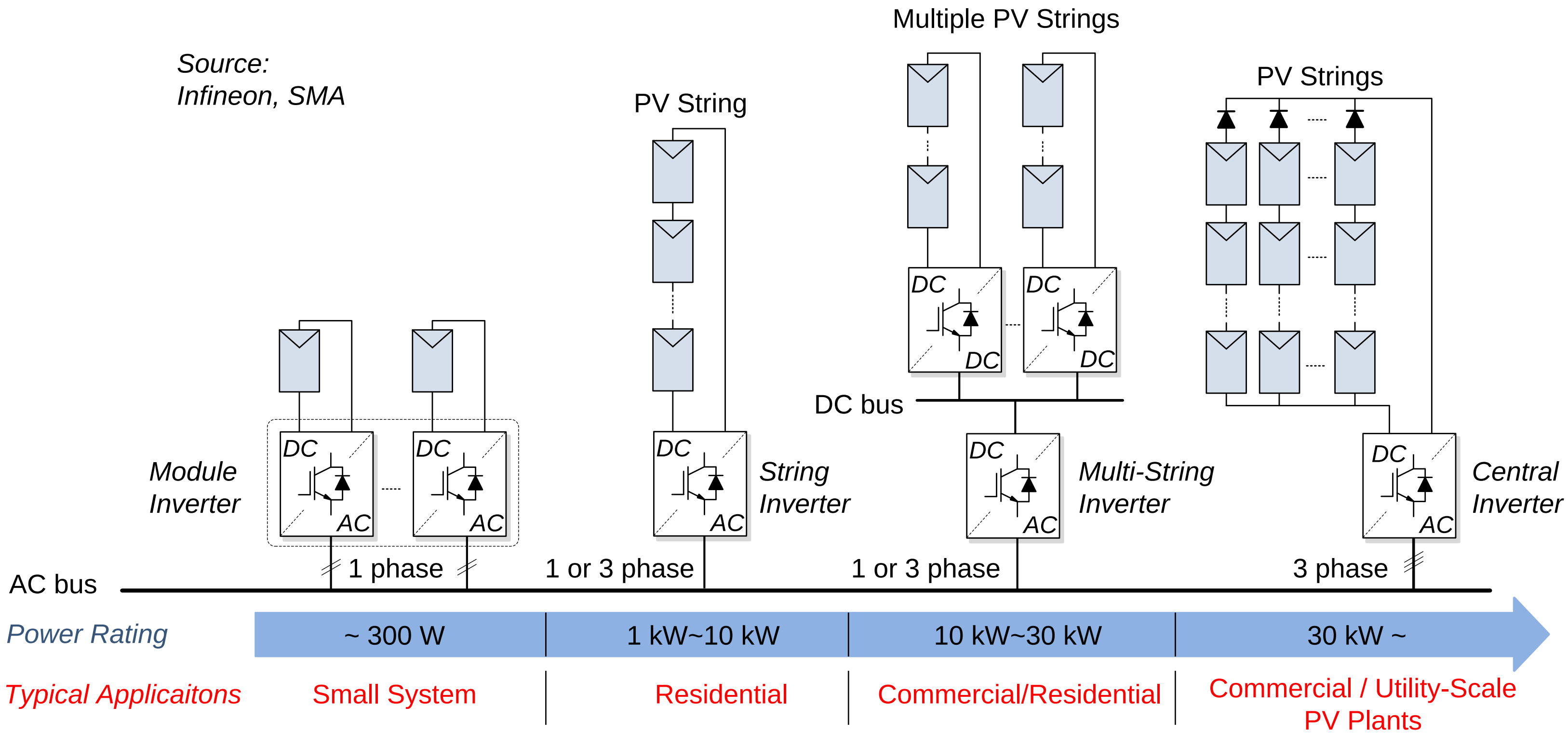
1. Controllable *I/U*

1. High efficiency
2. Low common mode *I*
3. Temp. insensitive
4. Reliable

1. Low THD

General Requirements & Specific Requirements

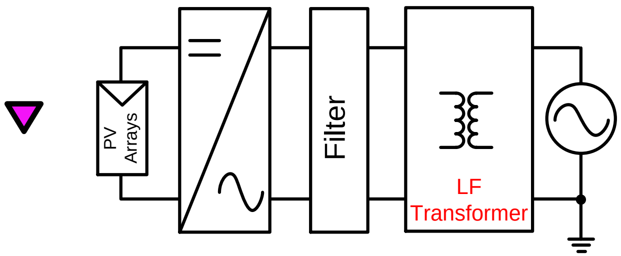
PV System Configurations

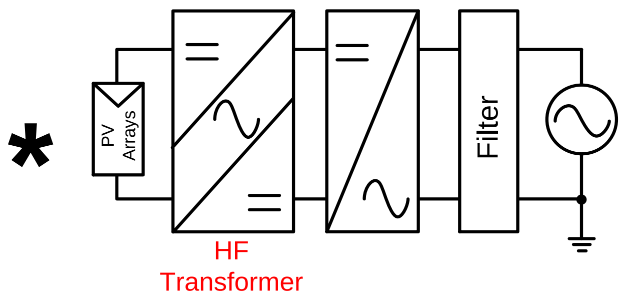


- **High efficiency mini-central (multi-string) PV inverters (8-15 kW) are also emerging for modular configuration in medium and high power PV systems**
- **Central inverters are available on market with very high power capacity (e.g. 750 kW by SMA)**
- **Transformerless PV inverters can achieve high efficiency with increasing popularity**

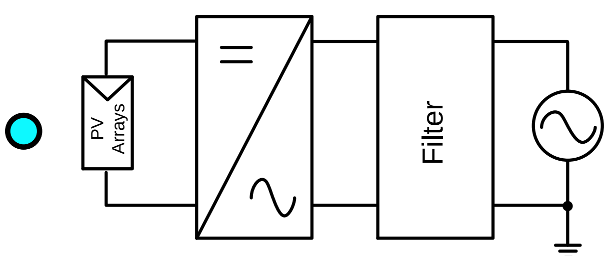
PV Inverters Market Survey

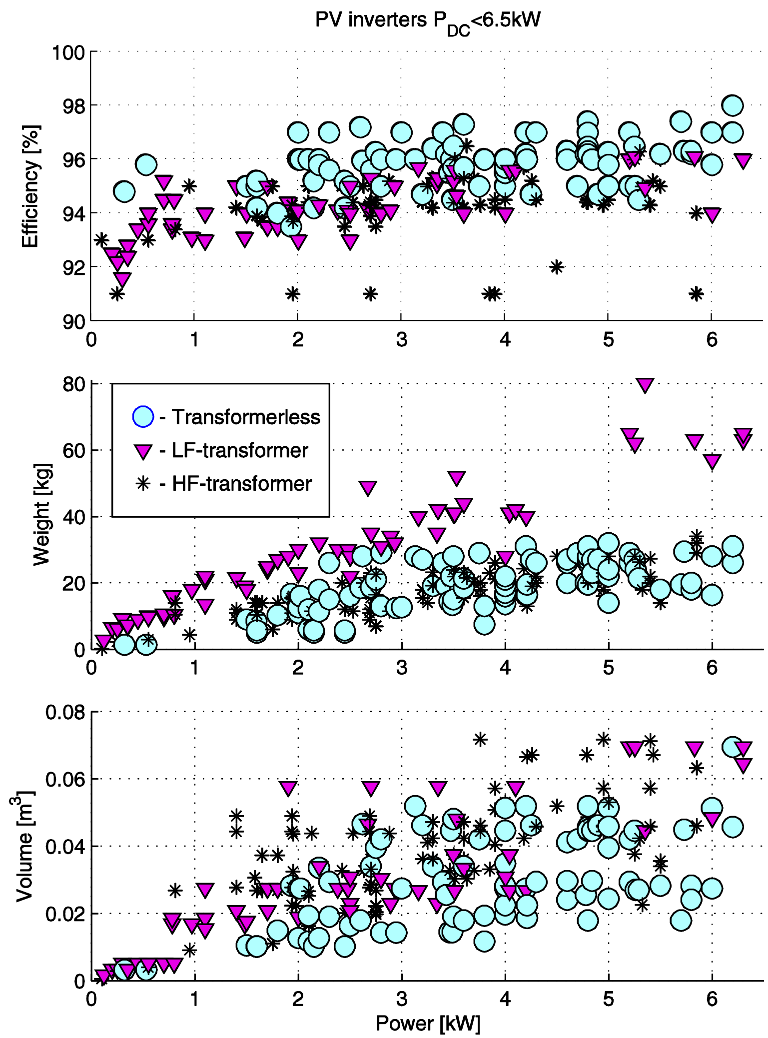
Transformer-based





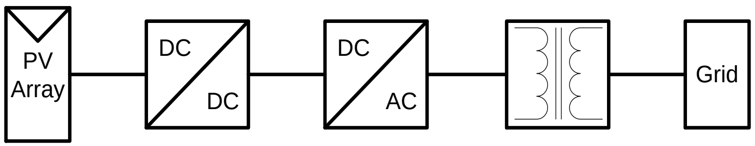
Transformerless-based



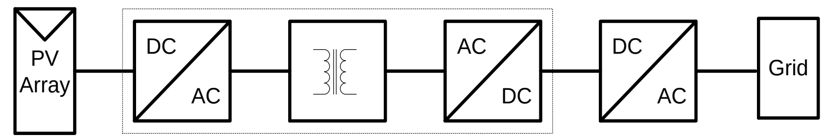


Source : Photon

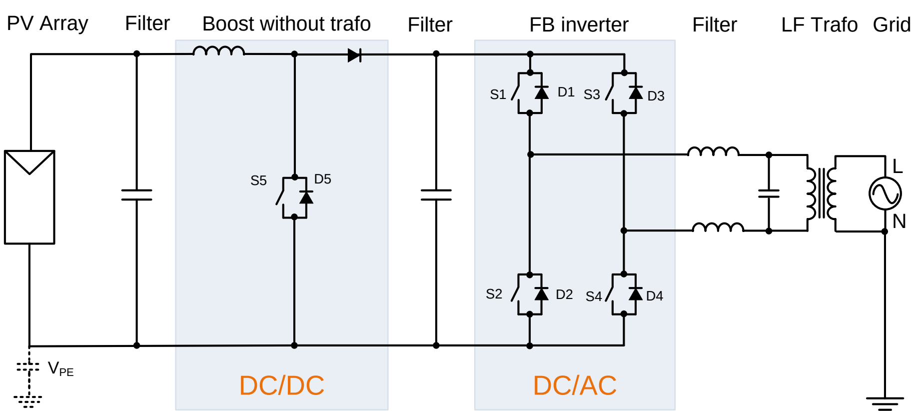
PV Inverters with Boost Converter and Isolation



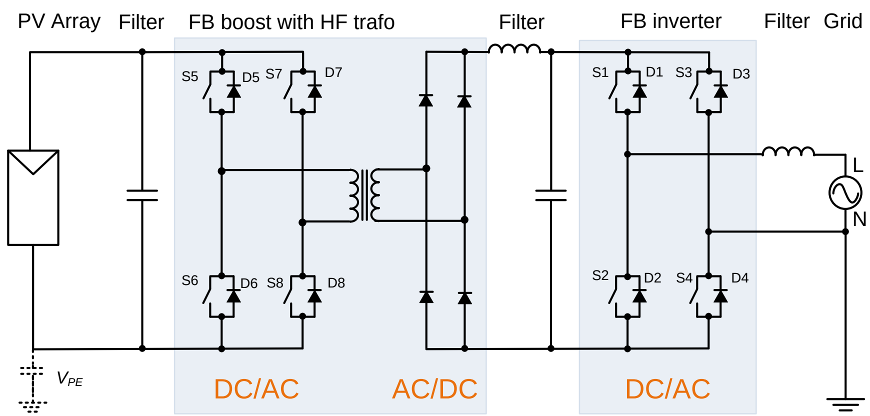
On Low Frequency (LF) Side



On High Frequency (HF) Side



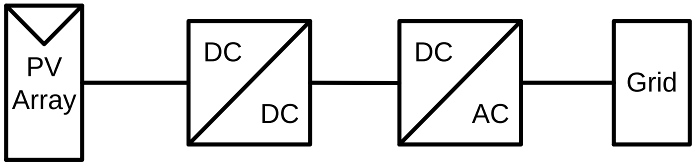
Boosting inverter with LF trafo based on boost converter



Boosting inverter with HF trafo based on FB boost converter

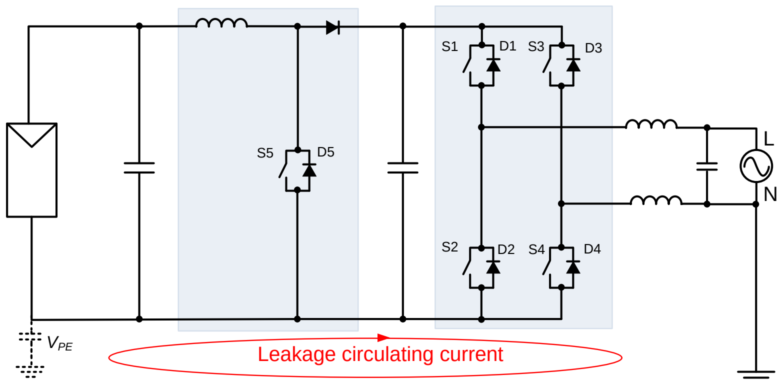
Both technologies are on the market! Efficiency: 93-95%

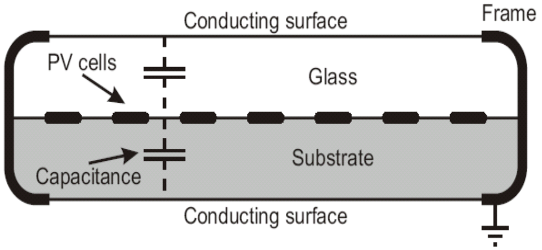
Transformerless PV Topologies with Boost Stage



Full Bridge Inverter with Boost Converter

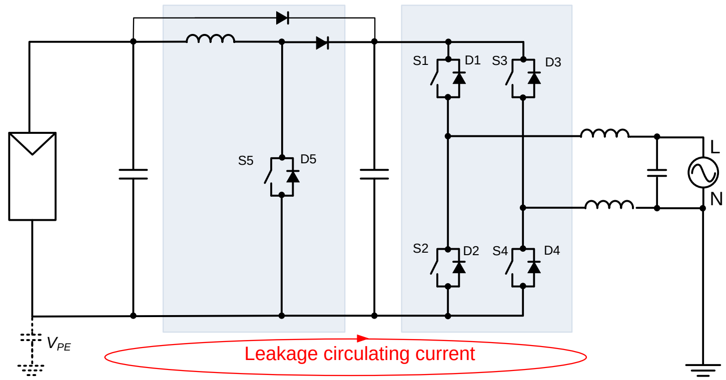
• Typical configuration

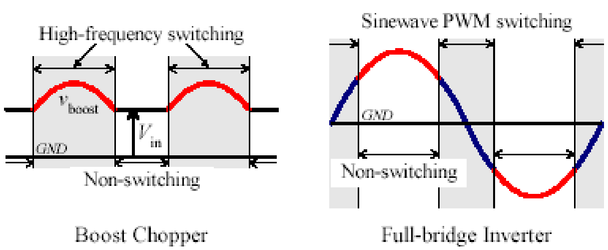




•High efficiency (>95%)
•Leakage current problem
•Safety issue

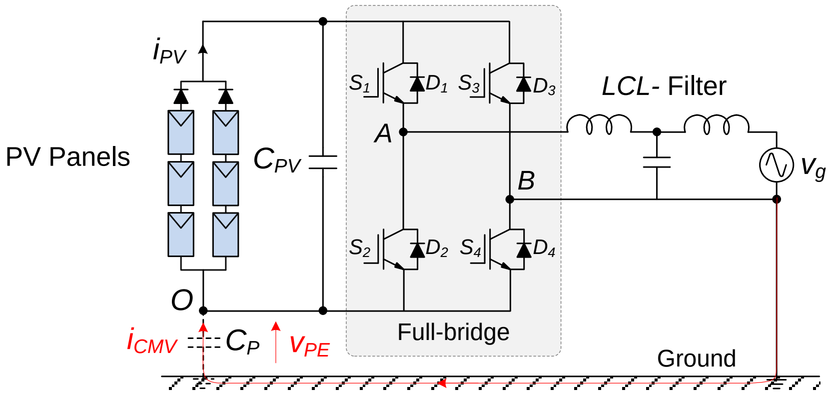
•Time sharing configuration





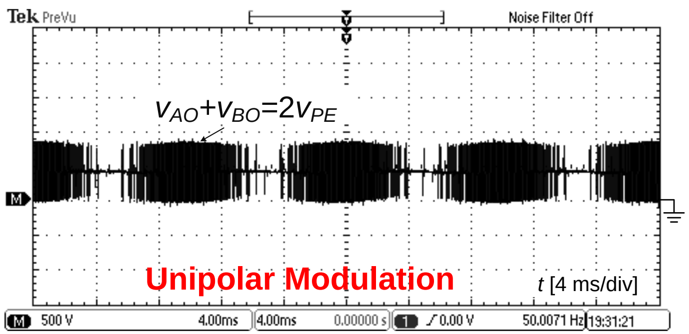
•Efficiency > 96%
•Extra diode to bypass boost when V_{pv} > V_g
•Boost with rectified sinus reference

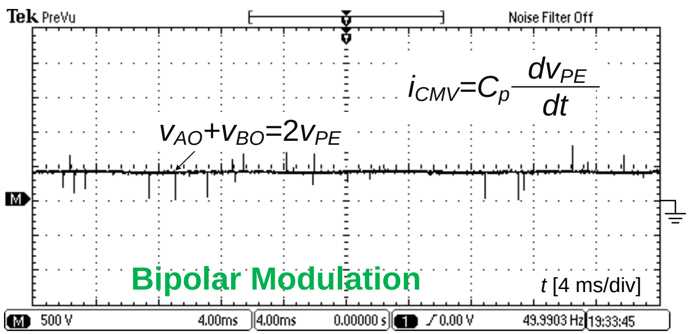
Single-Stage Transformerless PV Topology



Full Bridge Inverter with Different Modulation Schemes

- Unipolar Modulation
- Bipolar Modulation



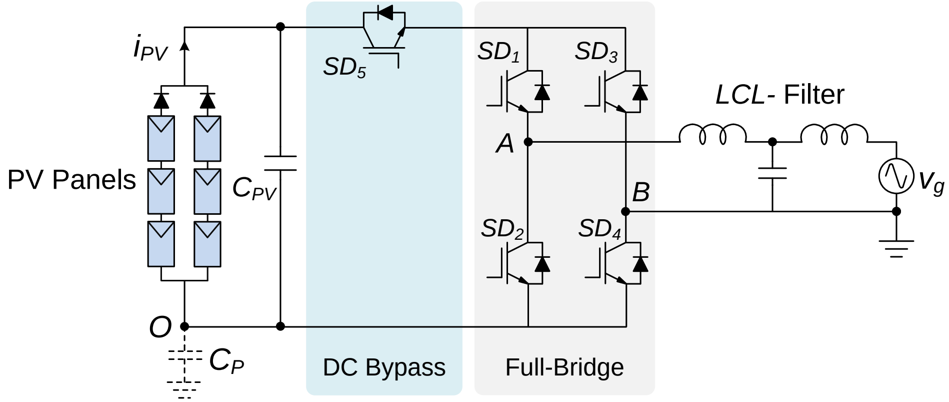


Bipolar Modulation

- No common mode voltage → V_{PE} free for high frequency →low leakage current
- Max efficiency 96.5% due to reactive power exchange between the filter and C_{PV} during freewheeling and due to the fact that 2 switched are simultaneously switched every switching
- This topology is not special suited to transformerless PV inverter due to low efficiency!

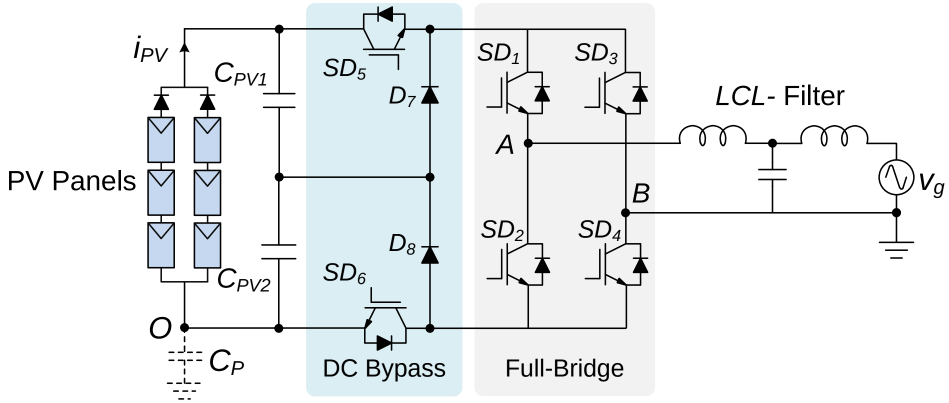
High Efficiency Transformerless PV Topologies

H5 Transformerless Inverter (SMA)



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

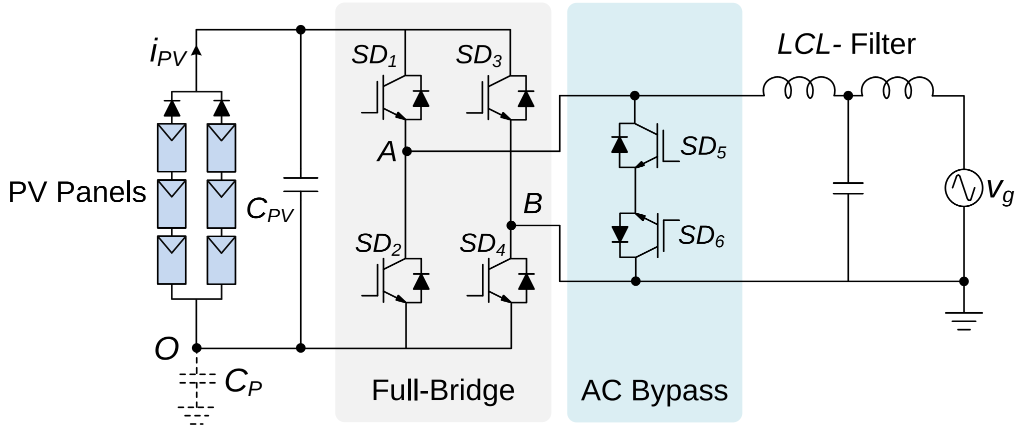
H6 Transformerless Inverter (Ingeteam)



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

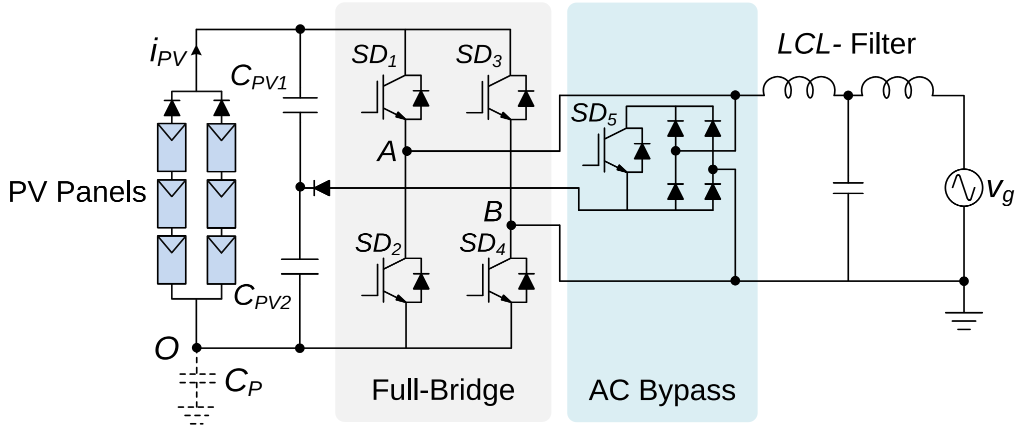
High Efficiency Transformerless PV Topologies

HERIC - Highly Efficient and Reliable Inverter Concept (Sunways)



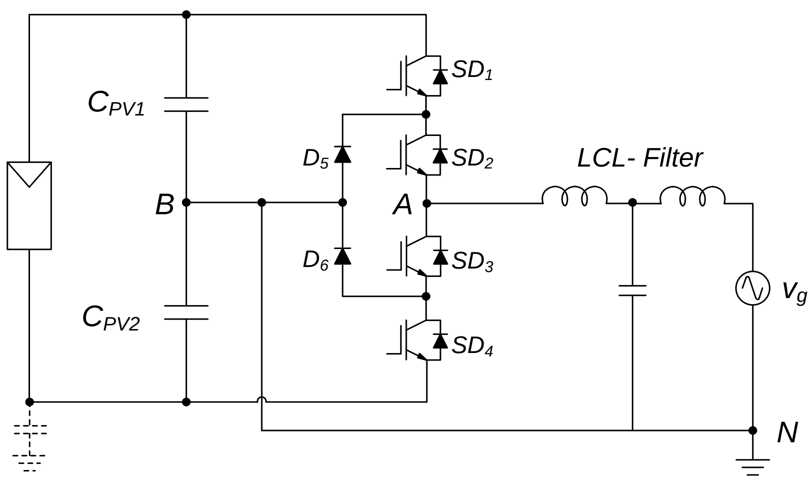
- High efficiency of up to 97%
- Very low leakage current and EMI
- Low core losses

FB-ZVR – Full Bridge with a Zero Voltage Rectifier (T. Kerekes, etc)

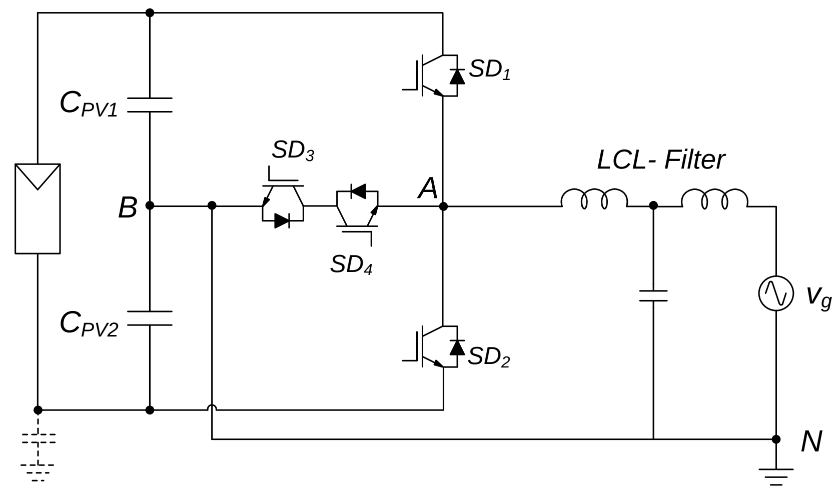


- Efficiency of up to 96%
- Low leakage current and EMI
- Unipolar voltage accross the filter, leading to low core losses

NPC Topologies for PV Applications



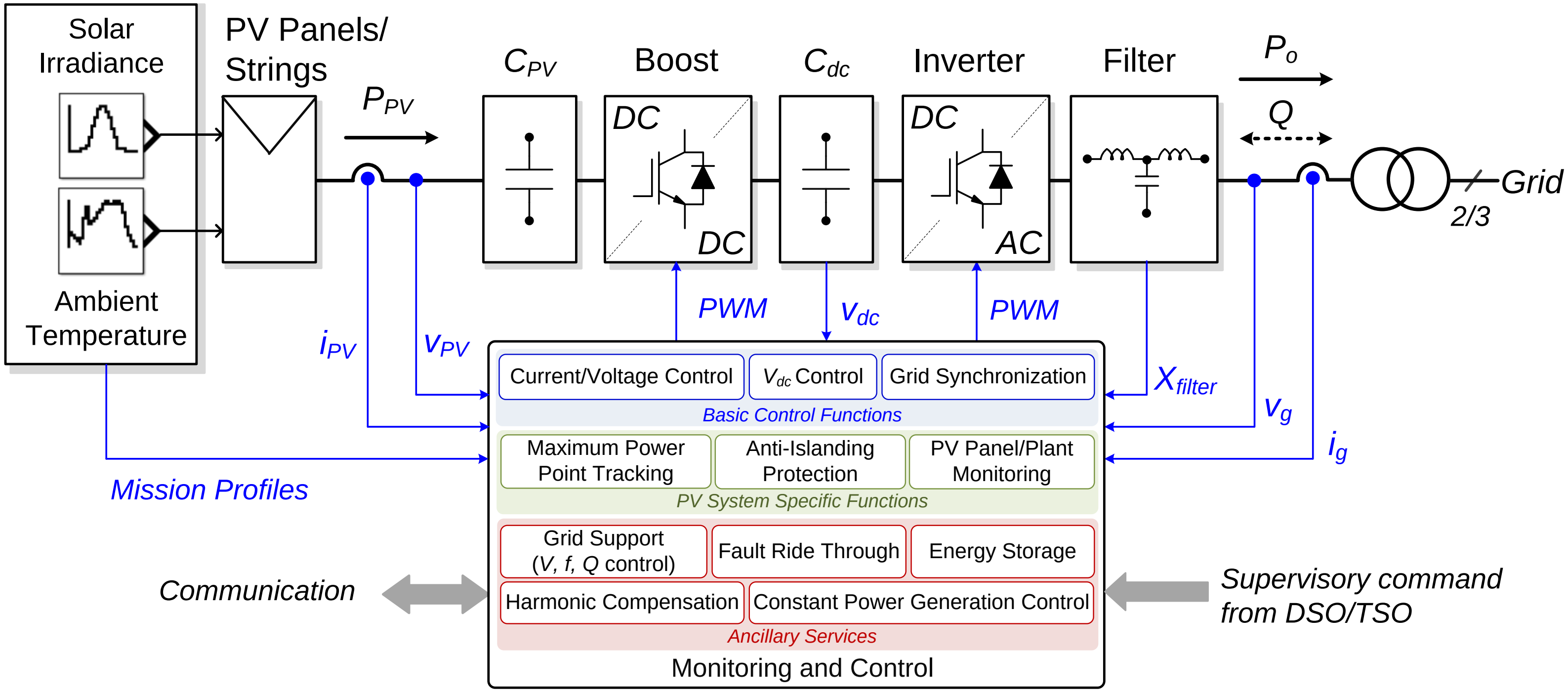
Neutral clampled half-bridge



Conergy neutral point clampled inverter

- **Three-level output. Requires double PV voltage input in comparison with FB.**
- **The switching ripple in the current equals 1x switching frequency → high filtering needed**
- **Voltage across filter is unipolar → low core losses**
- **V_{PE} is equal $-V_{pv}/2$ without high frequency component → low leakage current and EMI**
- **High max efficiency 98% due to no reactive power exchange, as reported by Danfoss Solar TripleLynx series (10/12.5/15 kW)**

Control Structure for a PV System



Basic functions – all grid-tied inverters

- Grid current control
- DC voltage control
- Grid synchronization

PV specific functions – common for PV inverters

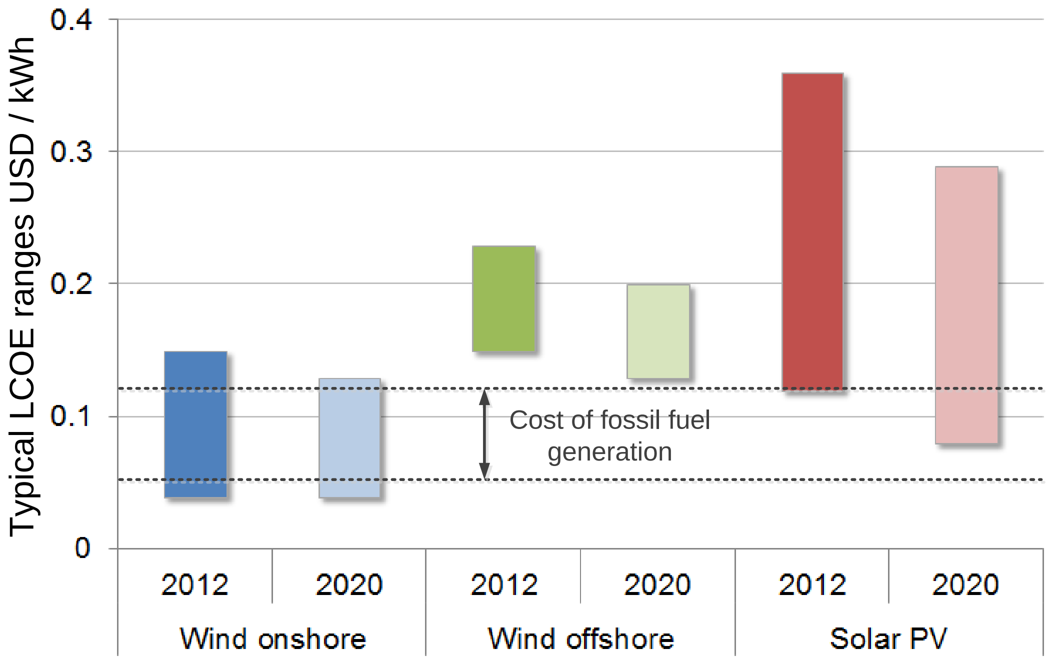
- Maximum power point tracking – MPPT
- Anti-Islanding (VDE0126, IEEE1574, etc.)
- Grid monitoring
- Plant monitoring
- Sun tracking (mechanical MPPT)

Ancillary support – in effectiveness

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

Challenge of Power Electronics in Renewable Energy Systems

Cost of Energy (COE)



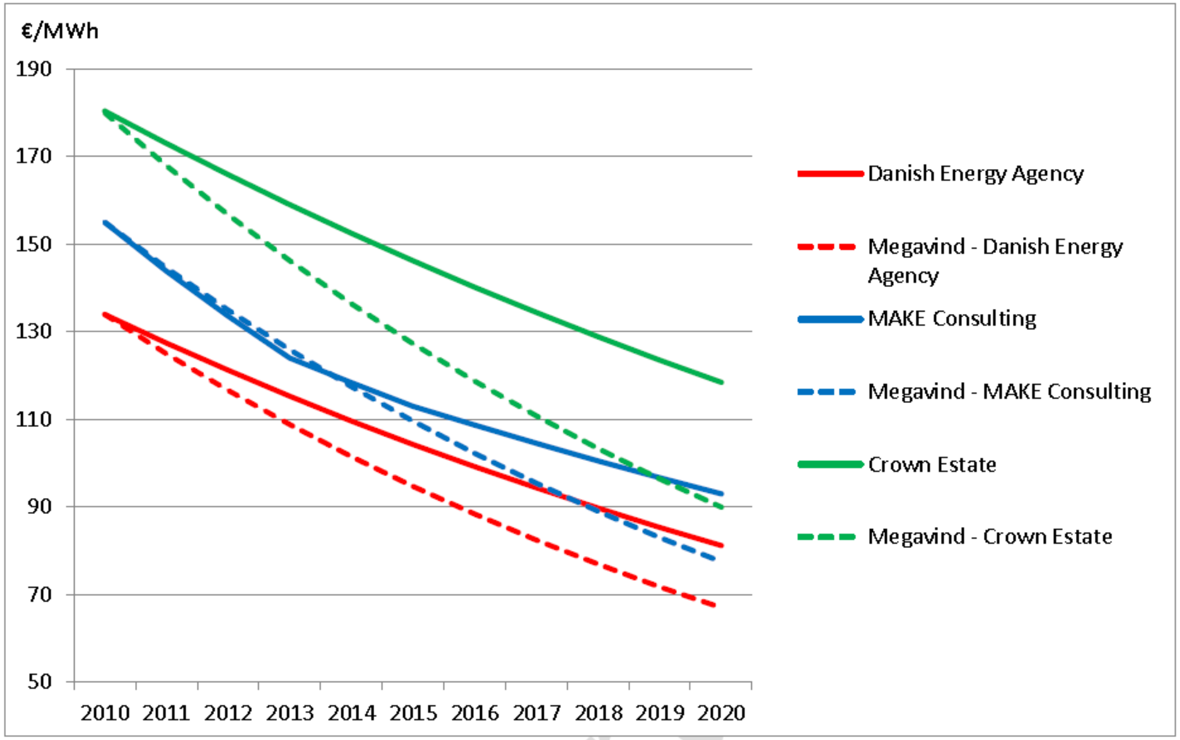
$$COE = \frac{C_{Cap} + C_{O\&M}}{E_{Annual}}$$

C_{Cap} – Capital cost
$C_{O\&M}$ – Operation and main. cost
E_{Annual} – Annual energy production

Determining factors for renewables

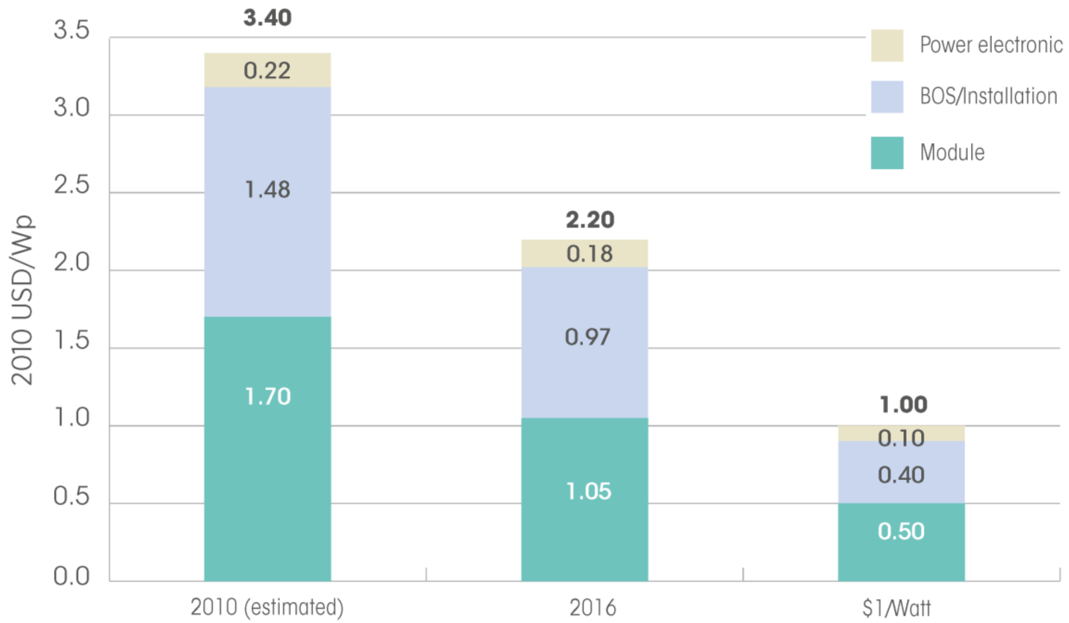
- **Capacity growth**
- **Technology development**

Needs for Lower Cost of Wind Power



Different trends
But the Cost of Energy will be reduced

Needs for Lower Cost of PV Power

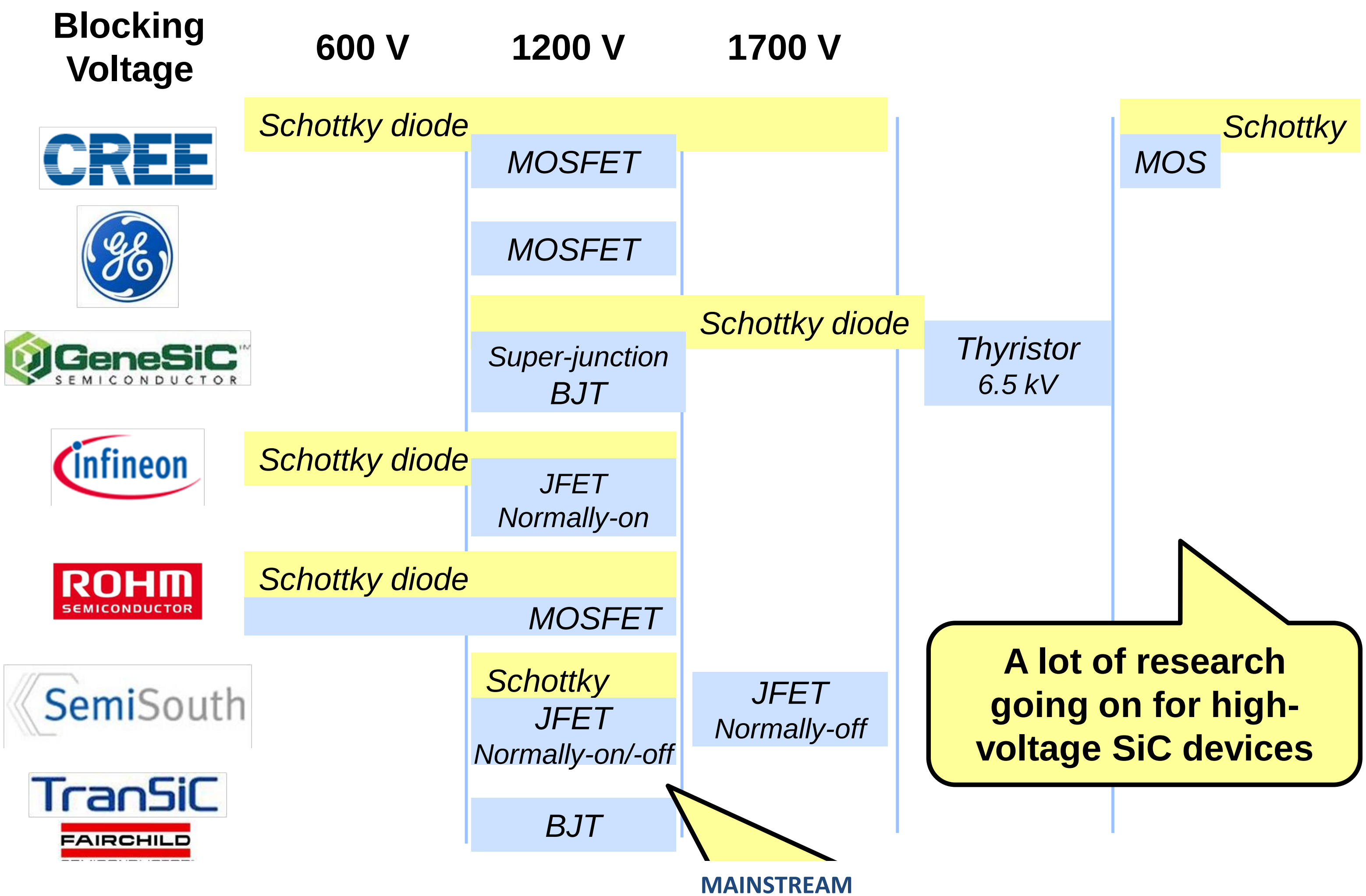


US DOE cost reduction goals to achieve $1/w by 2020.

(Source: Adapted from IRENA renewable energy technologies: cost analysis series -Solar Photovoltaics)

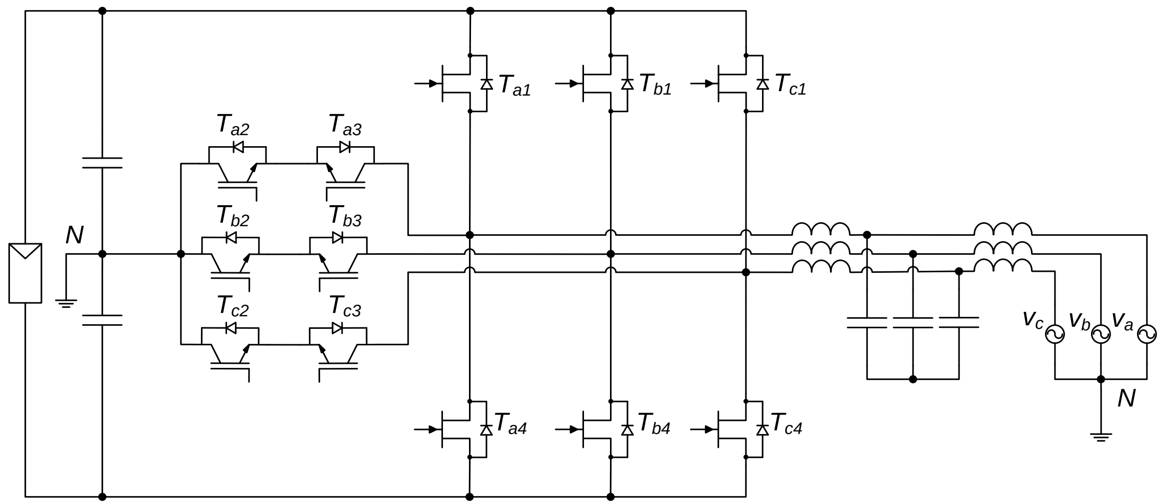
PV module cost should be reduced by 2/3
Power electronics needs also reduce cost by 1/2
Installation cost should be reduced by 2/3

SiC Devices



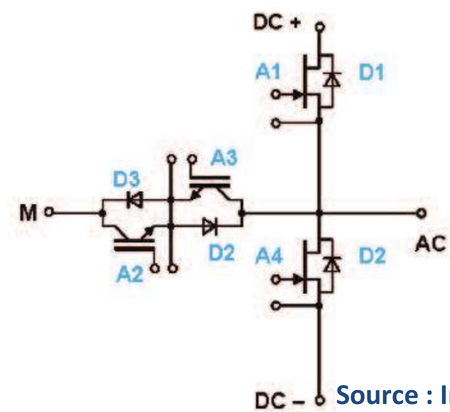
Source D, Boroyevich - CPES

First PV inverter based on SiC JFET



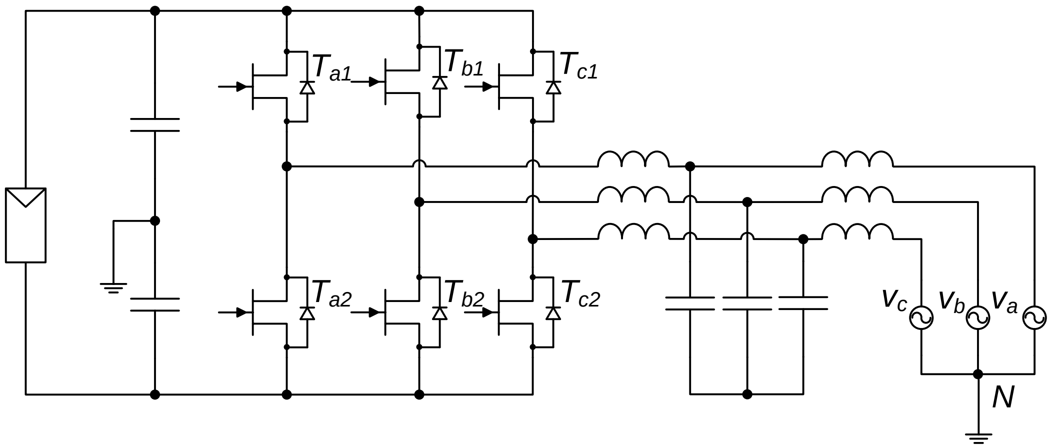
- SMA 20000TLHE-10 – 20 kW, 3 phase – 99.2%
- Light weight – 45 kg (1/2 of normal)
- Cooling minimized
- Conergy topology realized with Infineon modules
- SiC JFET with IGBT free whelling

Source Photon Intl – Dec 2011



Source : Infineon – Easy 1 b Modules

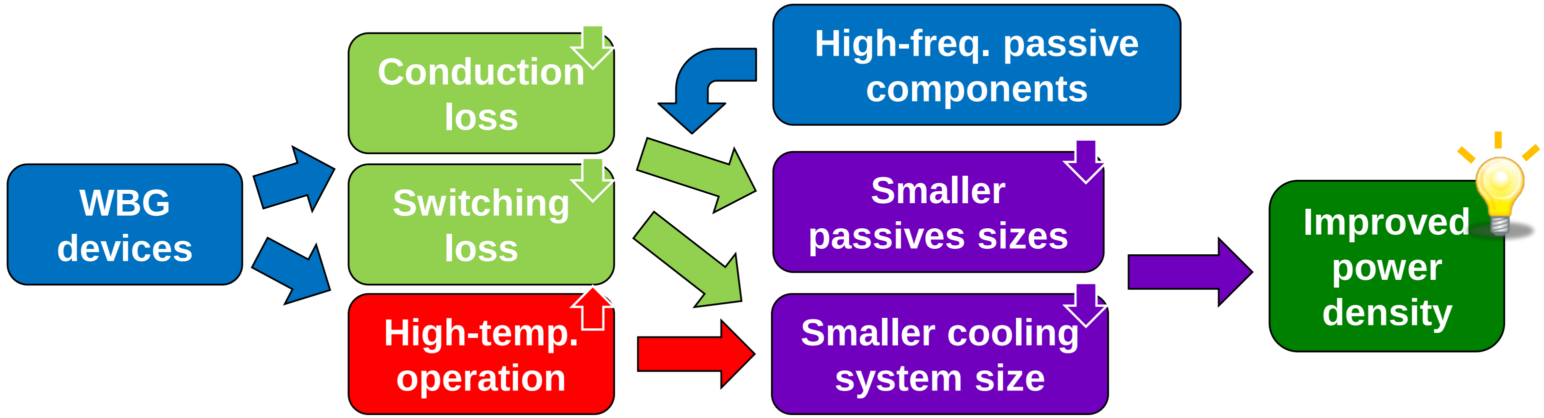
Simpler topologies with SiC JFET

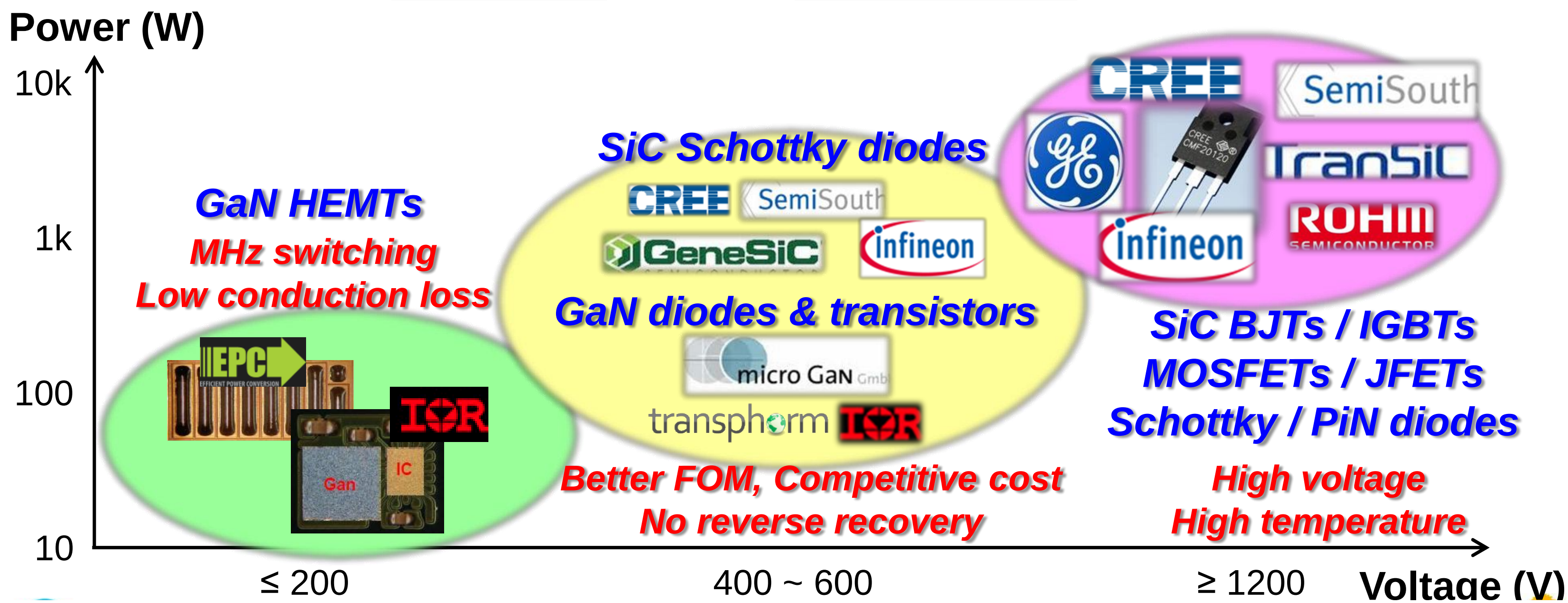


- Back to 2 level topologies!
- “Only” by doubling the switching frequency to 32 kHz, same efficiency of 98% as NPC-3L@16 kHz
- Half components count and lower footprint/weight
- Practical zero-reverse recovery with SiC diodes

Source B. Burger - Frunhofer

WBG Devices

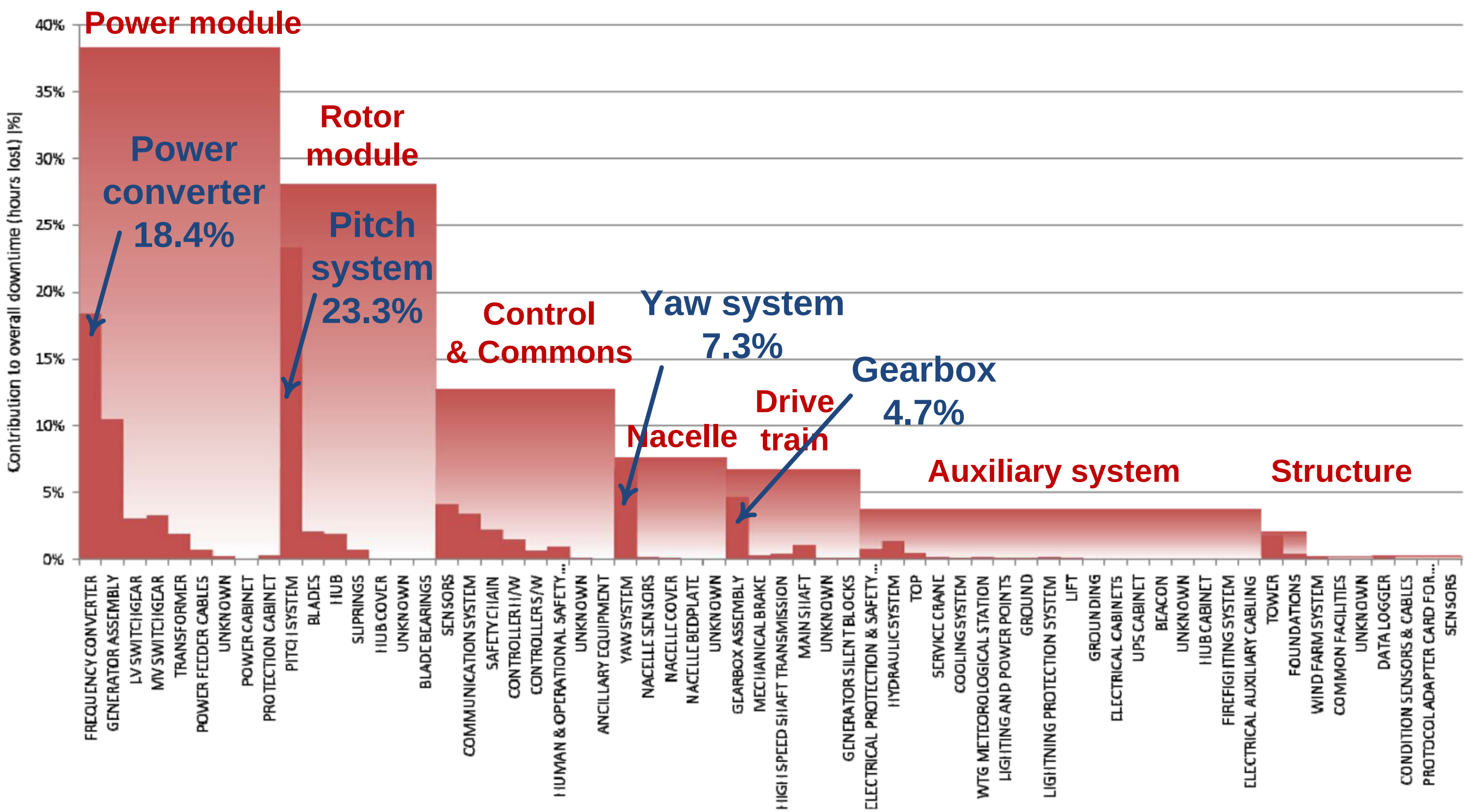




Source: D. Boroyevich - CPES

Failures of Power Electronic Systems

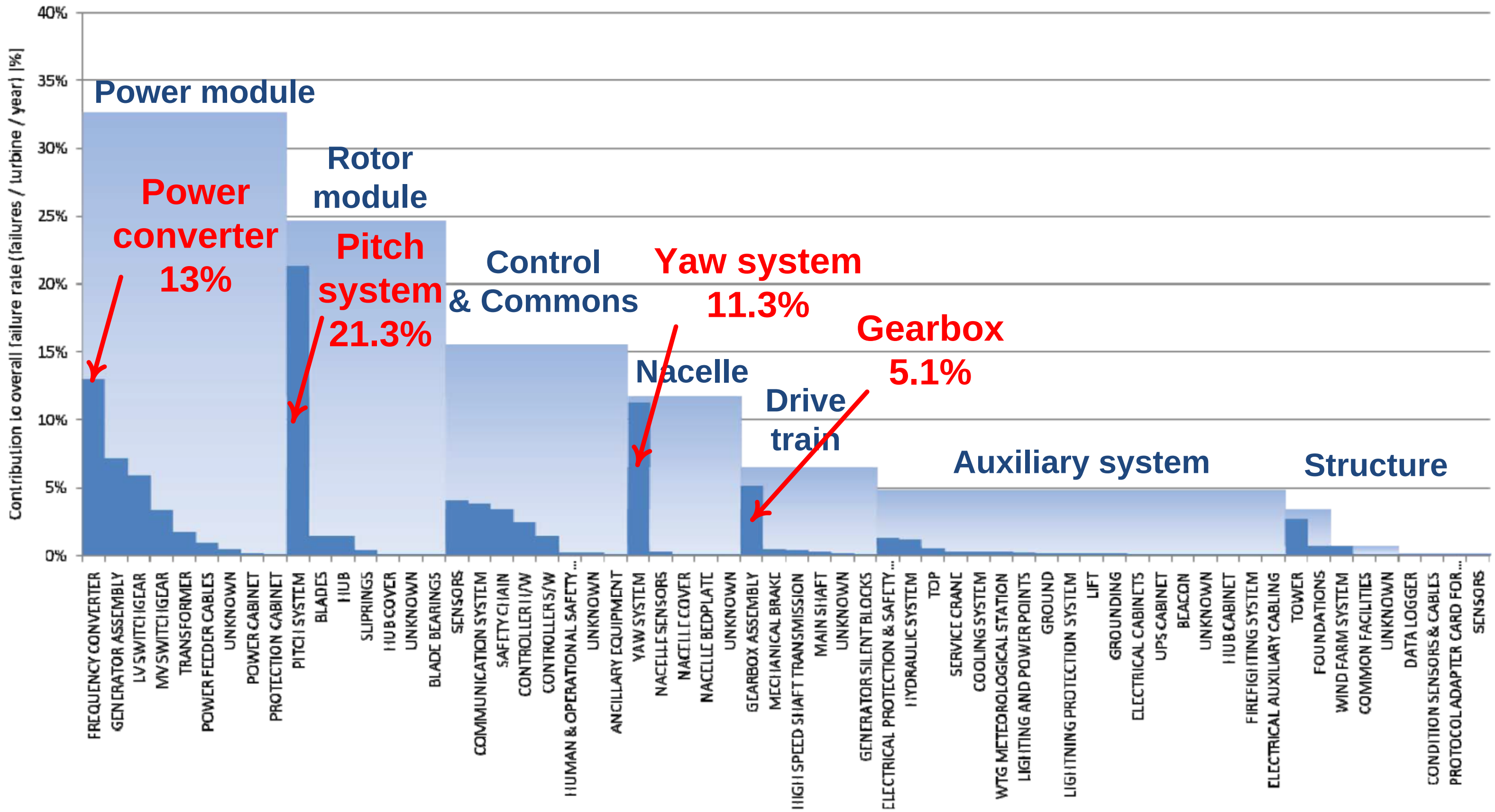
Field Experience of Wind Turbines – Normalized Downtime



(Source: Reliawind, Report on Wind Turbine Reliability Profiles – Field Data Reliability Analysis, 2011.)

Failures of Power Electronic Systems

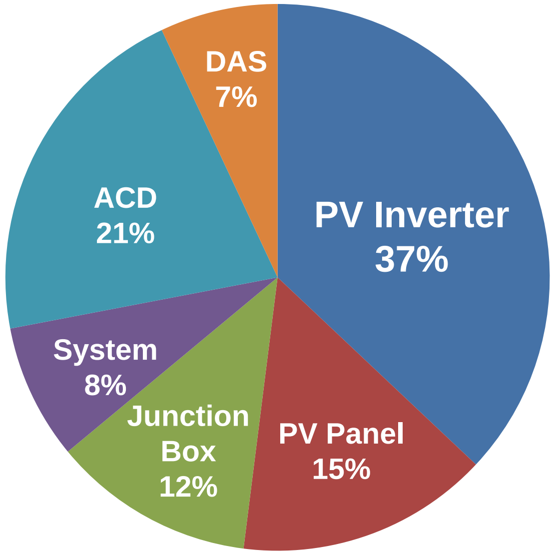
Field Experience of Wind Turbines – Normalized Failure Rate

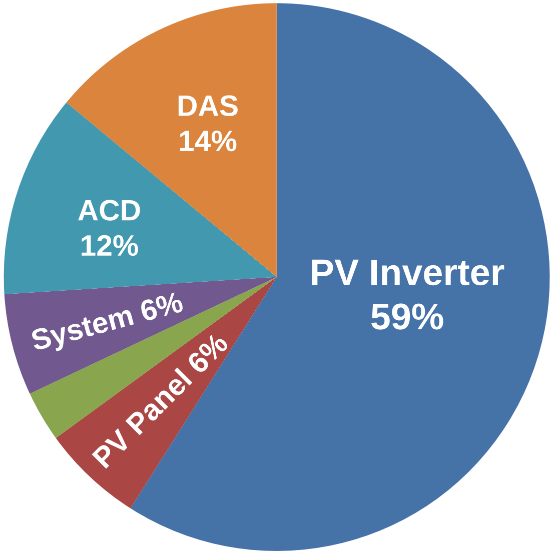


(Source: Reliawind, Report on Wind Turbine Reliability Profiles – Field Data Reliability Analysis, 2011.)

Failures of Power Electronic Systems

5 Years of Field Experience of a 3.5 MW PV Plant



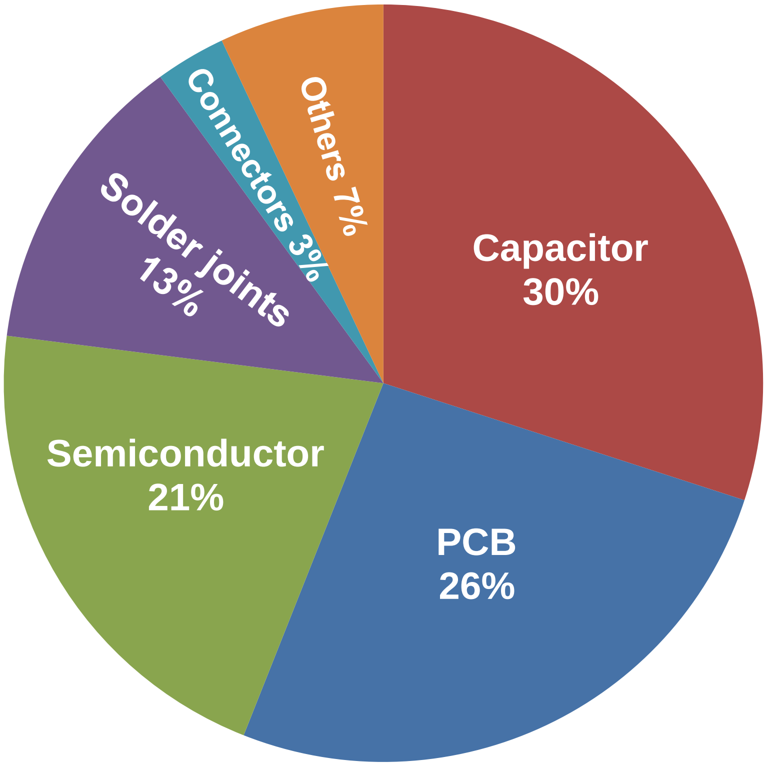


Unscheduled maintenance events by subsystem. **Unscheduled maintenance costs by subsystem.**

(ACD: AC Disconnects, DAS: Data Acquisition Systems)

(Data source: Moore, L. M. and H. N. Post, "Five years of operating experience at a large, utility-scale photovoltaic generating plant," Progress in Photovoltaics: Research and Applications 16(3): 249-259, 2008)

Critical Components in Power Electronic Systems



(www.abb.com)

(http://www.alibaba.com)

Failure root causes distribution for power electronic systems*
(% may vary for different applications and designs)

*Data sources: Wolfgang E., "Examples for Failures in Power Electronics Systems," in *EPE Tutorial 'Reliability of Power Electronic Systems'*, April 2007.

Approaches to Reduce Cost-of-Energy

$$COE = \frac{C_{Cap} + C_{O\&M}}{E_{Annual}}$$

C_{Cap} – Capital cost

$C_{O\&M}$ – Operation and main. cost

E_{Annual} – Annual energy production

Approaches	*Important and related factors*	*Potential*
Lower C_{Cap}	Production / Policy	+
Lower $C_{O\&M}$	Reliability / Design / Labor	++
Higher E_{annual}	Reliability / Capacity / Efficiency / Location	+++

Reliability is an efficient way to reduce COE – lower $C_{O\&M}$ & higher E_{annual} !

Shift of Reliability Analysis Approaches for PE

Product Drivers for Reliable Power Electronics

Emerging and critical applications

Harsh environments

Reduction of Cost-of-Energy (COE)
Increase of power density

→

Paradigm Shift in Research

Handbook calculations
Testing to pass

↓

Physics-of-failure approach
Design for reliability

→

More reliable and cost-effective power electronic systems

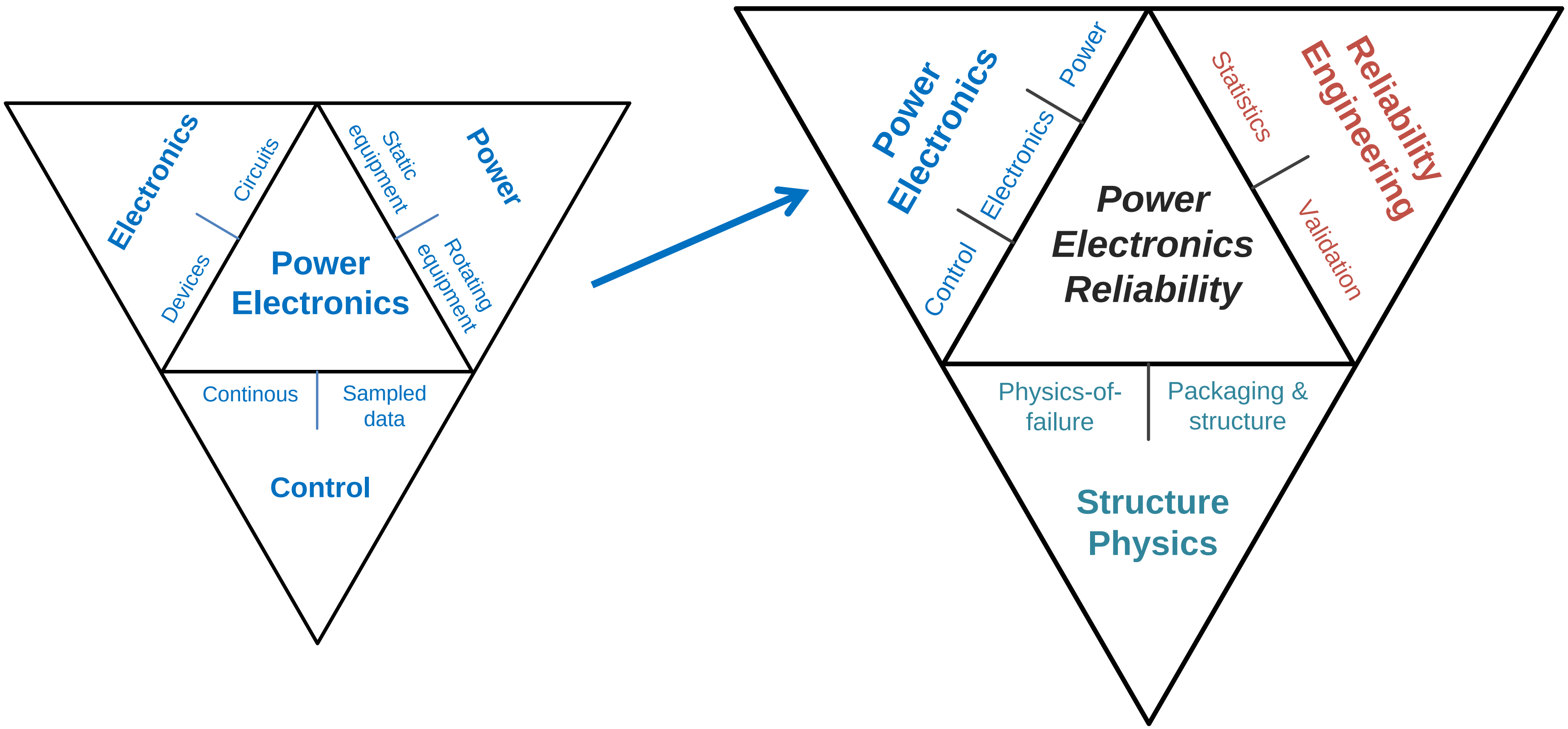
Reliability analysis of PE in the past

- Less dependent on mission profile
- Observations and statistics based
- Handbook/guideline calculation
- Testing under harsh conditions
- Hard to predict and control

Reliability analysis of PE in the future

- More considerations of mission profile
- Root cause based
- Failure mechanism modeling
- Robustness validations
- More predictable and controllable

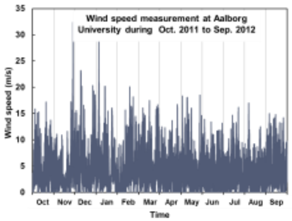
Multi-disciplines for physics-of-failure approach

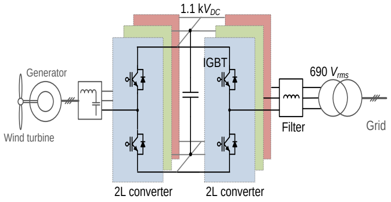


In 1974, William E. Newell defined power electronics as a technology based on multi-disciplines.

Physics-of-failure approach for power electronics reliability is also based on multi-disciplinary knowledge.

Reliability prediction of power electronics





Mission Profile

Converter Design

Stress Analysis

- Mission analysis
- Load estimation
- ...

Loading profile

Strength Modeling

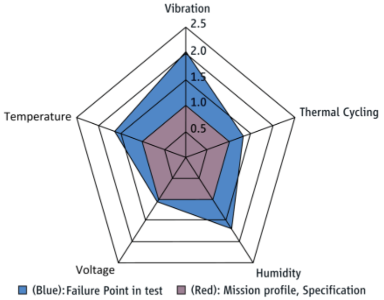
- Failure mechanism
- Accelerating test
- Field feedback
- ...

Lifetime

Variation & Statistics

- System combination
- Stress/devices variation
- Production robustness
- ...

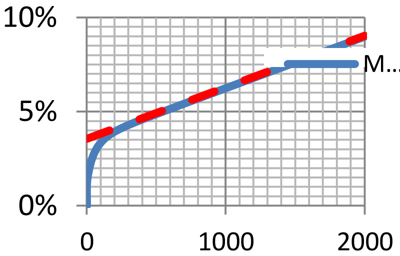
Reliability information



Robustness margins

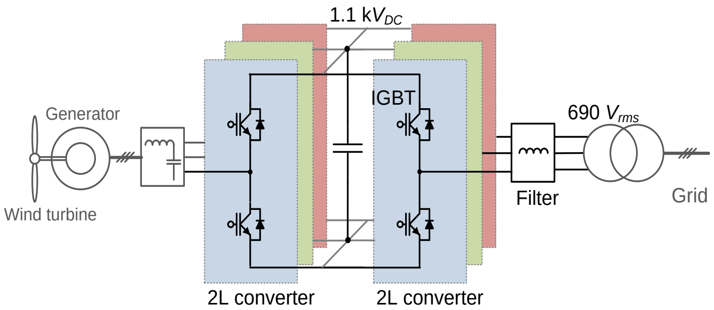
Failure sites	B_{10} lifetime (year)	
	Selection I	*Section II*
Baseplate solder joints (due to ΔT_c)	358	24
IGBT chip solder joints (due to ΔT_{j_IGBT})	438	22
Wire bonds (due to ΔT_{j_IGBT})	2633	74
Overall (determined by the shortest one)	**358**	**22**

Lifetime



Mean cumulative failure rate (MCF) Curve

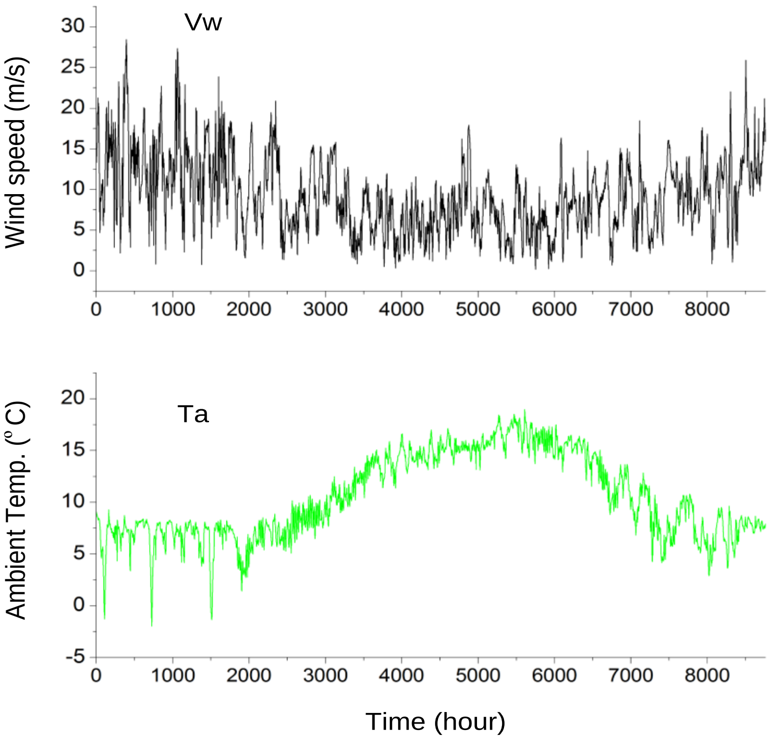
Lifetime prediction of IGBT in wind power converter



Rated output active power P_o	2 MW
DC bus voltage V_{dc}	1.1 kV DC
*Rated primary side voltage V_p	690 V rms
Rated load current I_{load}	1.93 kA rms
Fundamental frequency f_o	50 Hz
Switching frequency f_c	1950 Hz
Filter inductance L_f	132 µH (0.2 p.u.)

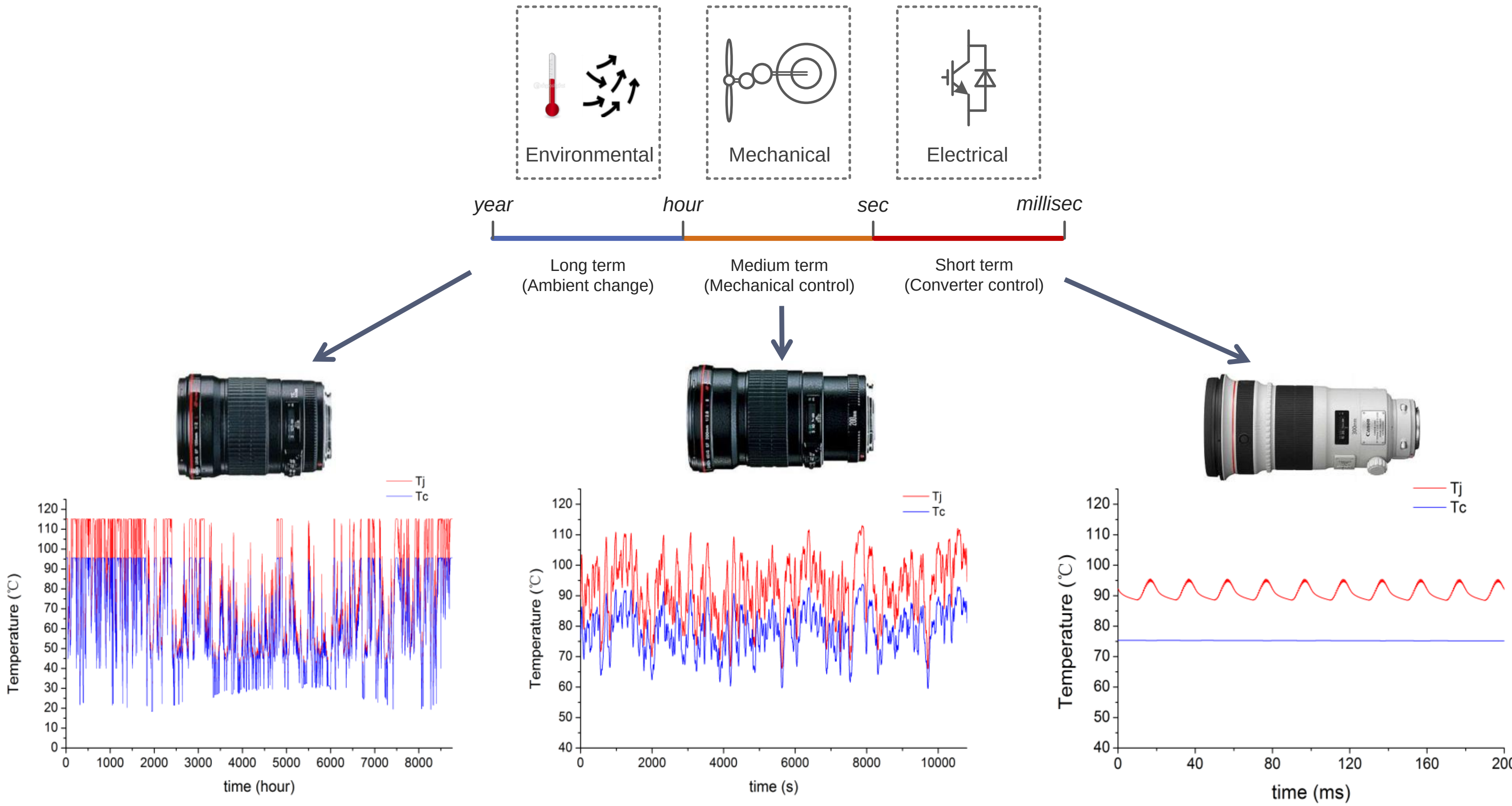
* Line-to-line voltage in the primary windings of transformer.

Converter design



Wind and temperature profile –mission profiles.

Thermal stress of IGBT in different time-scales in WTS



1 year, 3 hours step | **3 hours, 1 second step** | **0.2 second, 0. 01 millsec step**

- **Thermal stress is focused under different details and time constants.**
- **Just like the lenses with different focus lengths in photography.**

Procedure for lifetime estimation of wind power converter

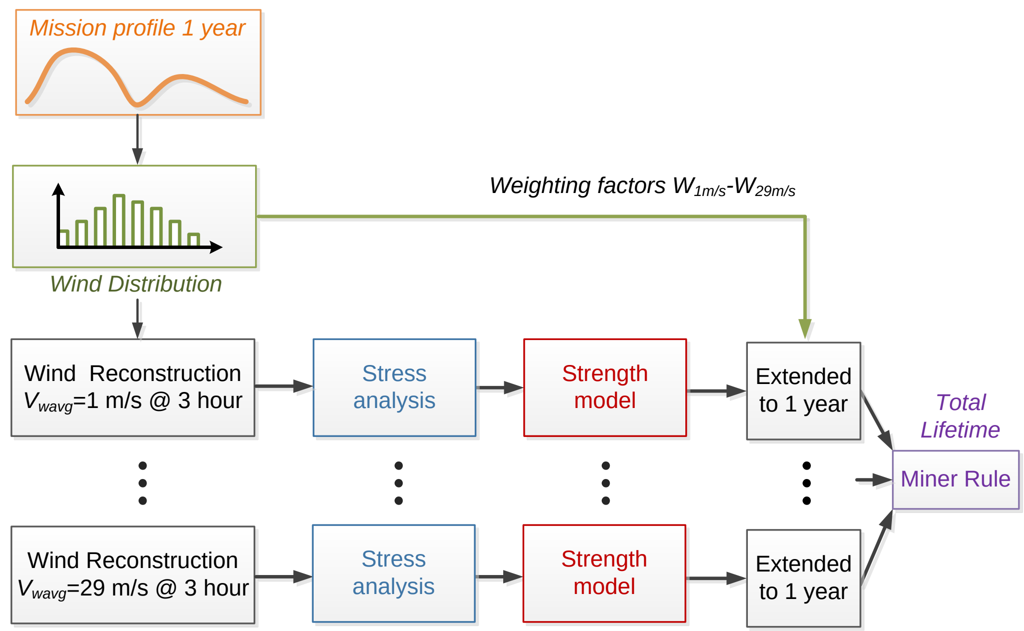
Long-term lifetime estimation:

- **Influenced by environmental change.**
- **Long term analysis up years.**
- **Larger time step are needed.**
- **Mission profile is translated to device lifetime.**

Time span : 1 year, Step: 3 hours

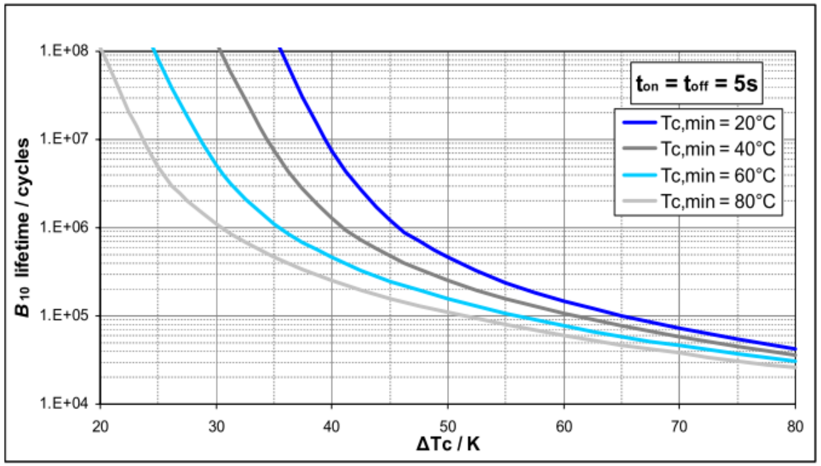
Medium- & short- term lifetime estimation:

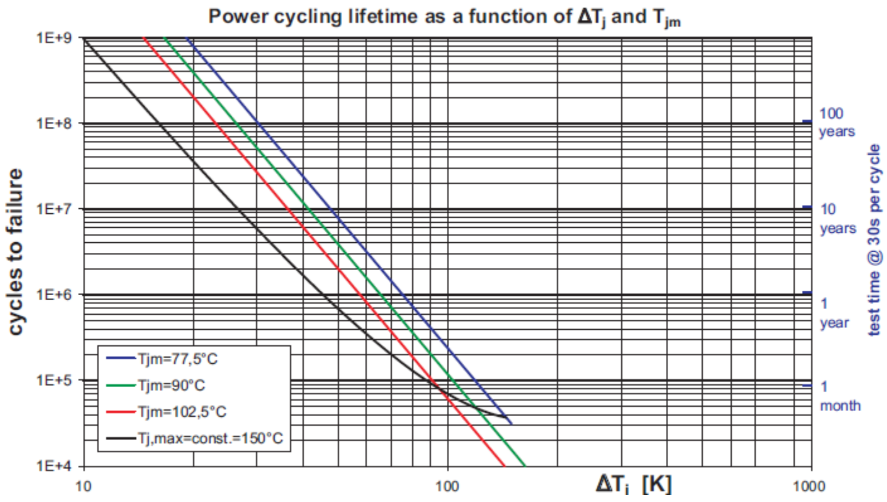
- **Influenced by mechanical behavior.**
- **Medium term analysis - hours.**
- **Moderate time step - seconds.**
- **More detailed models are necessary.**



Time span: 3 hours, step: 1 second

Strength models of IGBT (cycles to certain failure rate)

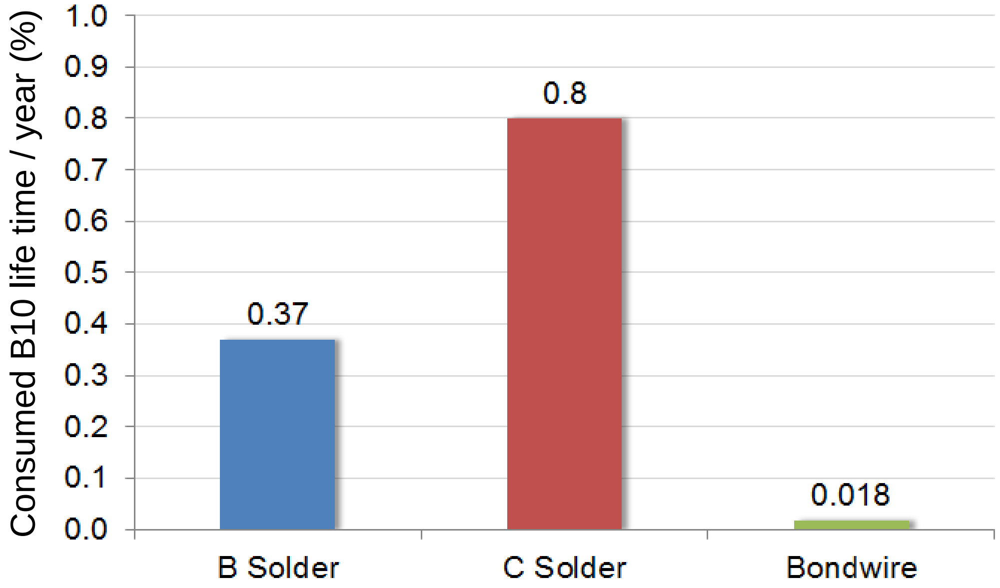




Life time model from ABB

Life time model from Semikron

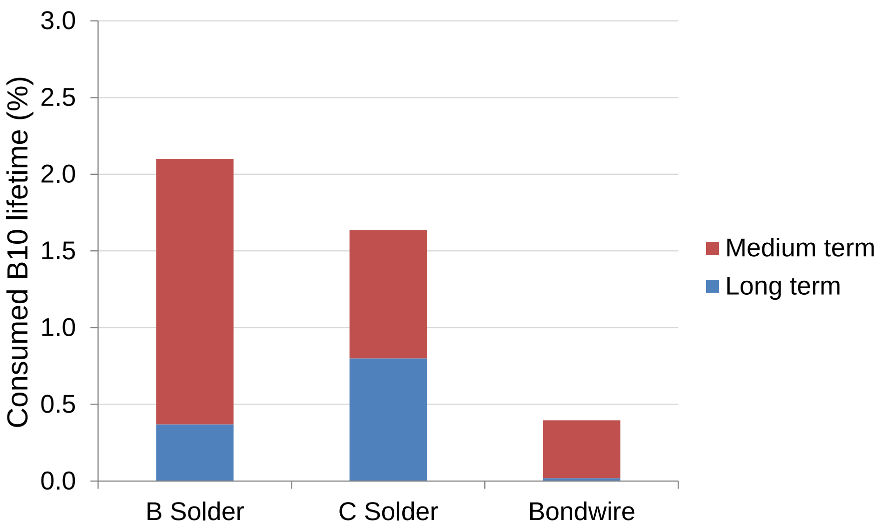
Lifetime of IGBT by long term thermal loading

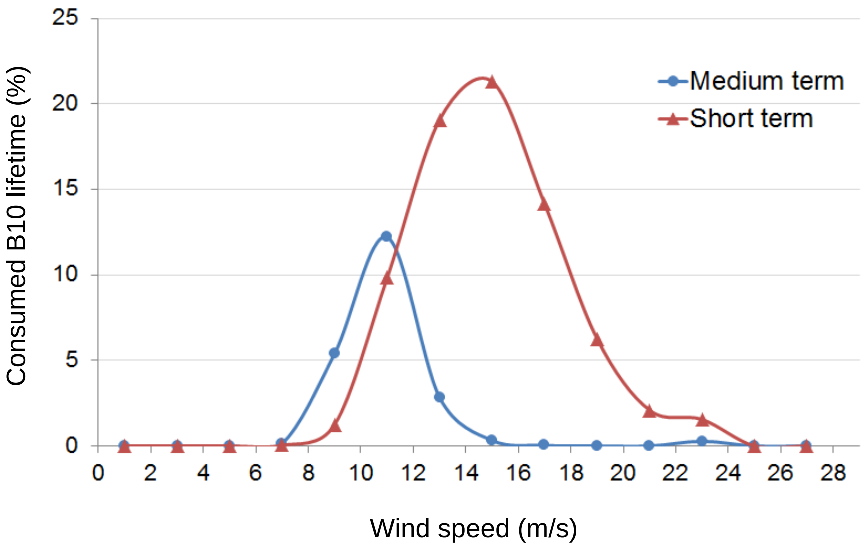


Consumed life time vs.
different failure mechanisms.

- **B solder – Baseplate solder failures.**
- **C solder – Chip solder failures.**
- **Bondwire – Bond wire failures.**
- **B10 life time – Lifetime when device has 10 % failure rate.**

Summary of lifetime estimation in different time scales





Consumed life time vs. different failure mechanisms.

Consumed life time vs. different wind speeds.

Summary

Power Electronics for renewable energy : Wind Turbines and Photovoltaic Systems

- A solution for the long term future in society
- Cost of Energy should be further reduced
- Increased power production close to the consumption place
- Coordinated control of production and consumption
- Future grid configurations may be different – but intelligent
- Systems should be able to run in on-grid and off-grid modes
- PV-plants will get same specifications as wind turbines
- Wind turbines have been the fastest growing in MW but PV will come
- Wind turbine technology – better performance
  - Full scale power electronics
  - New generator concepts (e.g. PM, gearless)
  - Larger size – lower cost per kWh
  - Reliability – a key to lower cost of Energy

Power Electronics

enabling renewable energy into an intelligent grid

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