Power Electronics – Quo Vadis

Frede Blaabjerg

Professor, IEEE Fellow
fbl@et.aau.dk

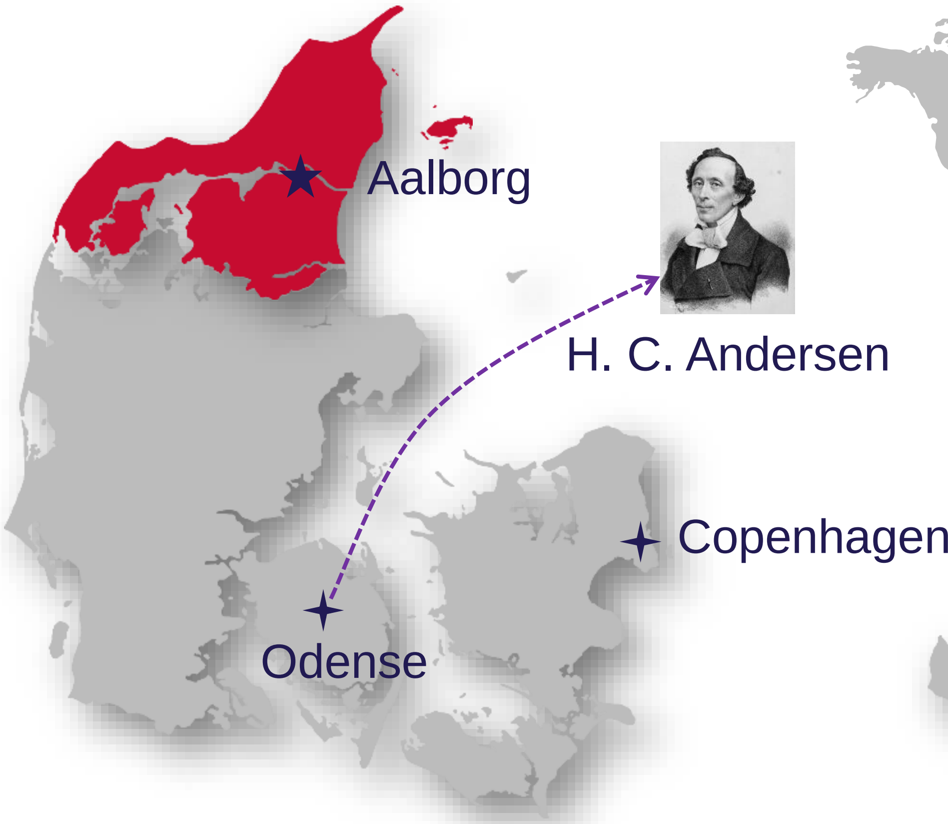
Aalborg University
Department of Energy Technology
Aalborg, Denmark

AALBORG UNIVERSITY
DENMARK

Outline

- **Power Electronics and Components**
  State-of-the-art; Technology overview, global impact
- **Renewable Energy Systems**
  PV; Wind power; Cost of Energy; Grid Codes
- **Reliable Power Electronics**
  Reliability, Design for reliability, Physics of Failure
- **Outlook**

► Aalborg University, Denmark

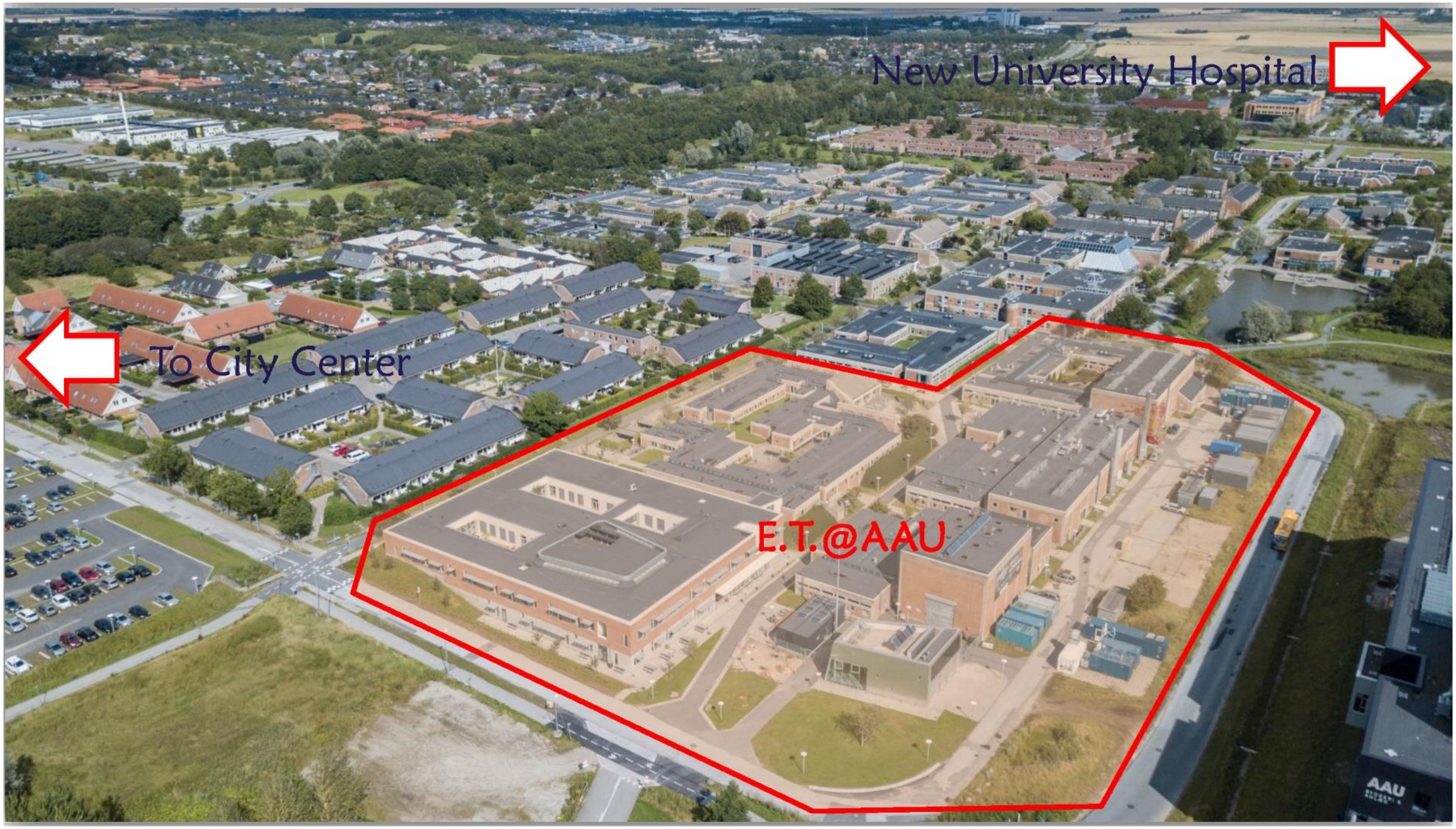


USNEWS 2019
Engineering
No. 4 globally
No. 1 in Europe
No. 1 in normalized citation impact globally
Source:
https://www.usnews.com/education/best-global-universities/engineering

Established in 1974
22,000 students
2,300 faculty

PBL-Aalborg Model
(Problem-based learning)

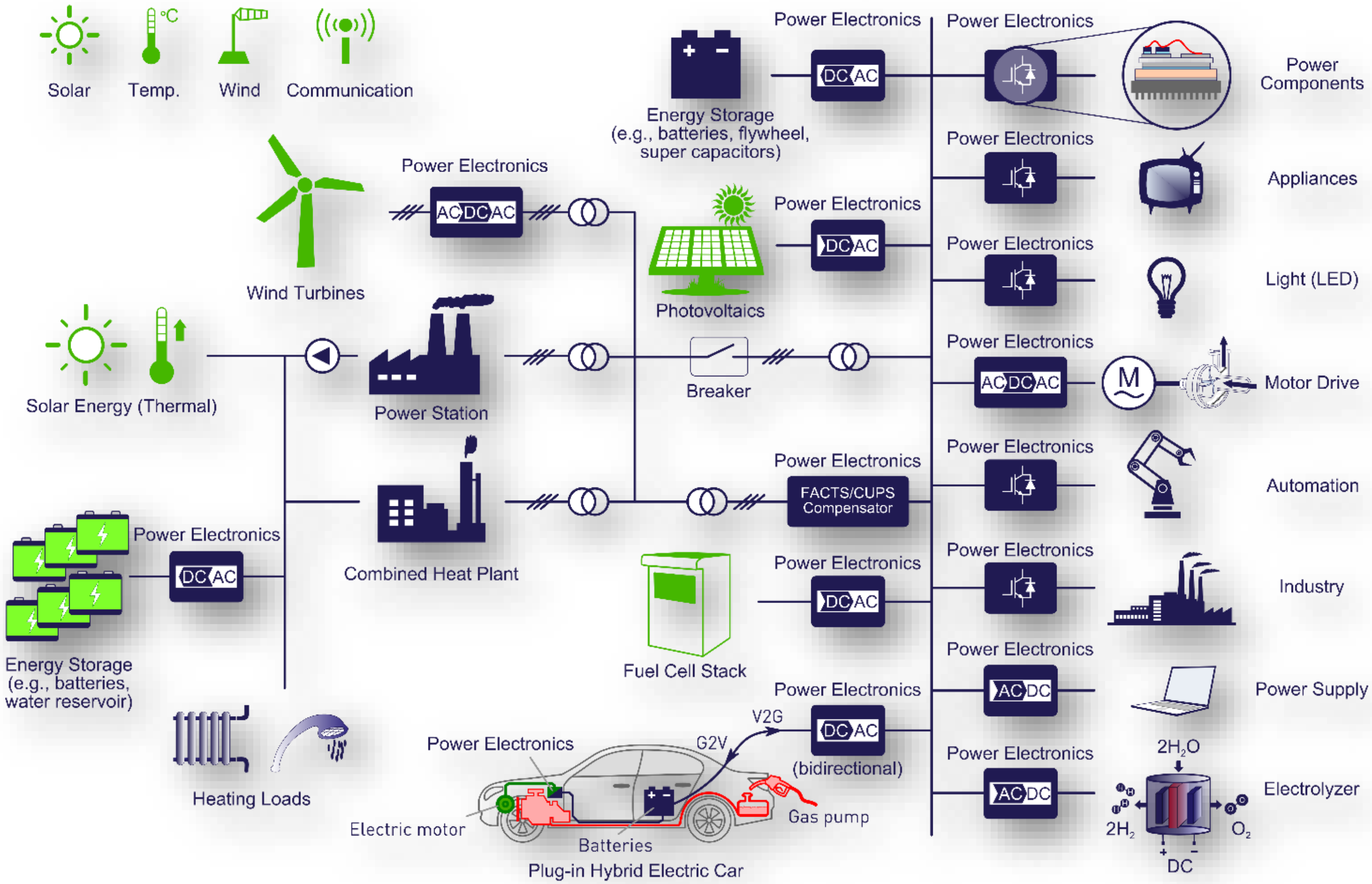
▶ Where are We Now?



► Energy Technology Department at Aalborg University

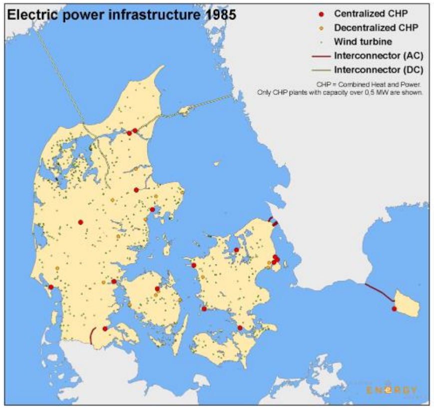
40+ Faculty, 120+ PhDs, 30+ RAs & Postdocs, 20+ Technical staff, 80+ visiting scholars

60% of manpower on power electronics and its applications



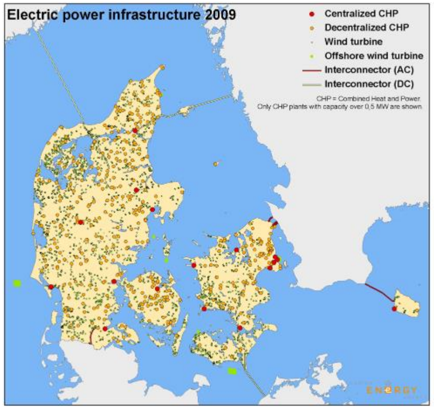
Power Electronics and Components

▶ 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**

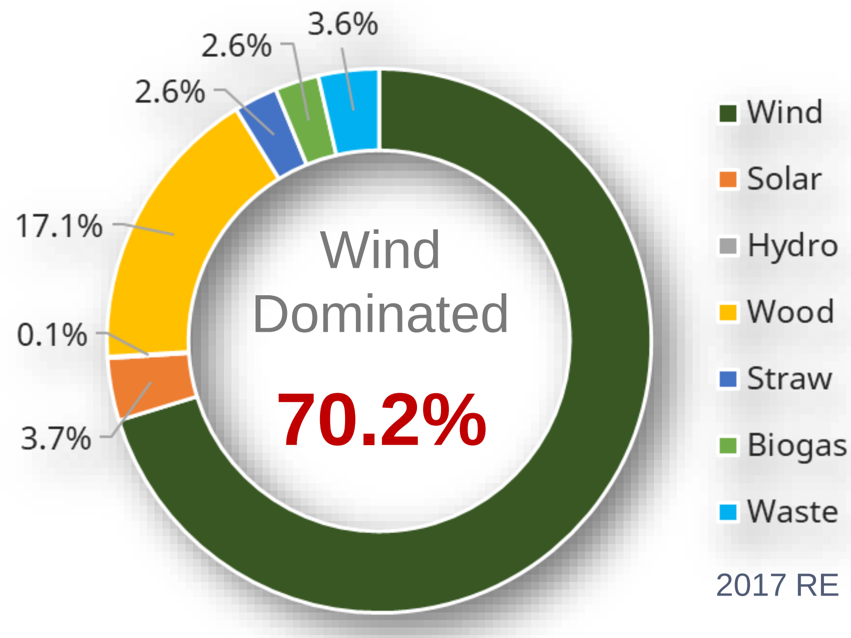
Source: http://media.treehugger.com

Source: www.offshorewind.biz

Towards 100% Power Electronics Interfaced

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

Renewable Electricity in Denmark



2017 RE Electricity Gener. in DK

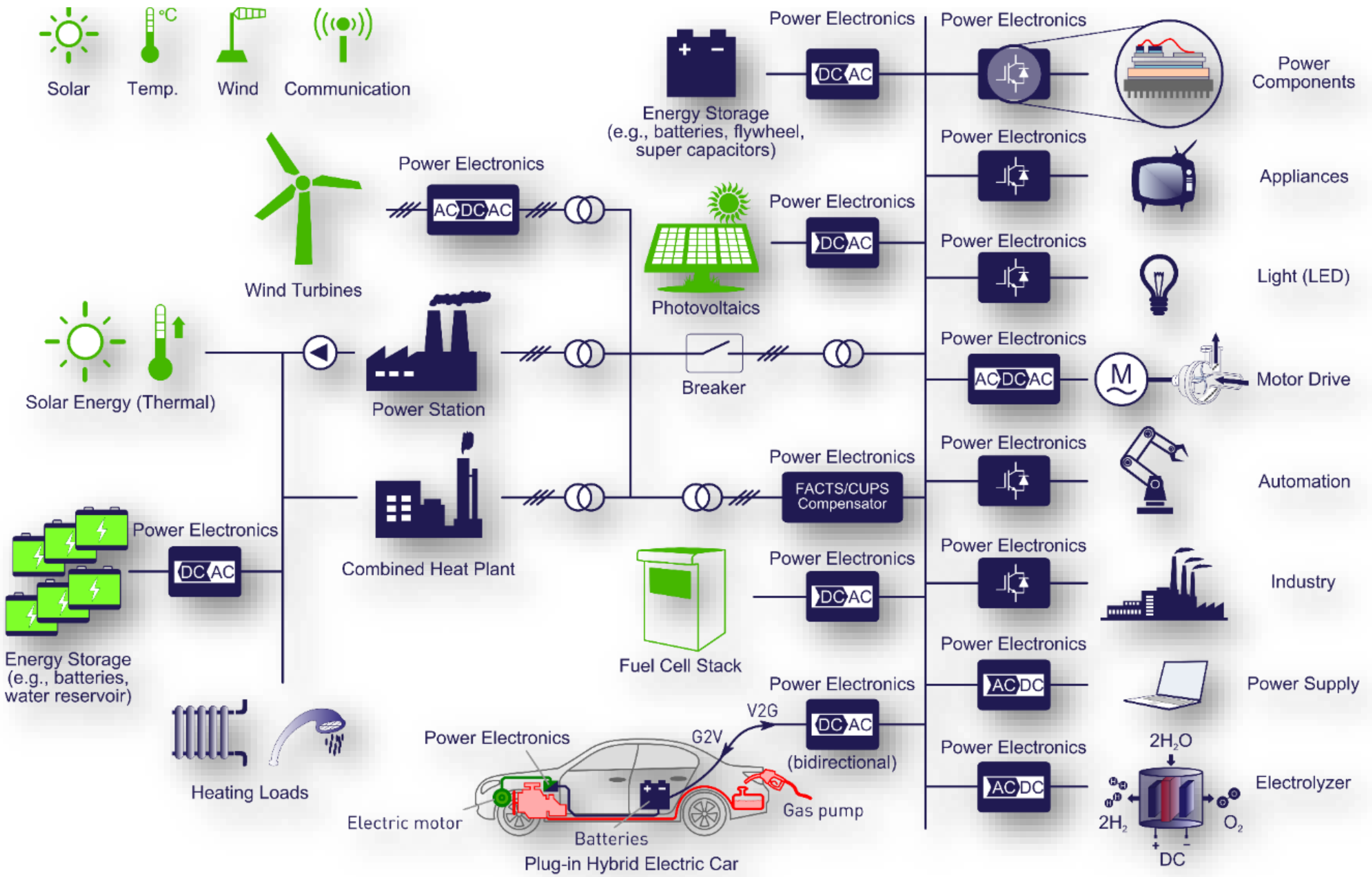
Proportion of renewable electricity in Denmark (*target value)

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

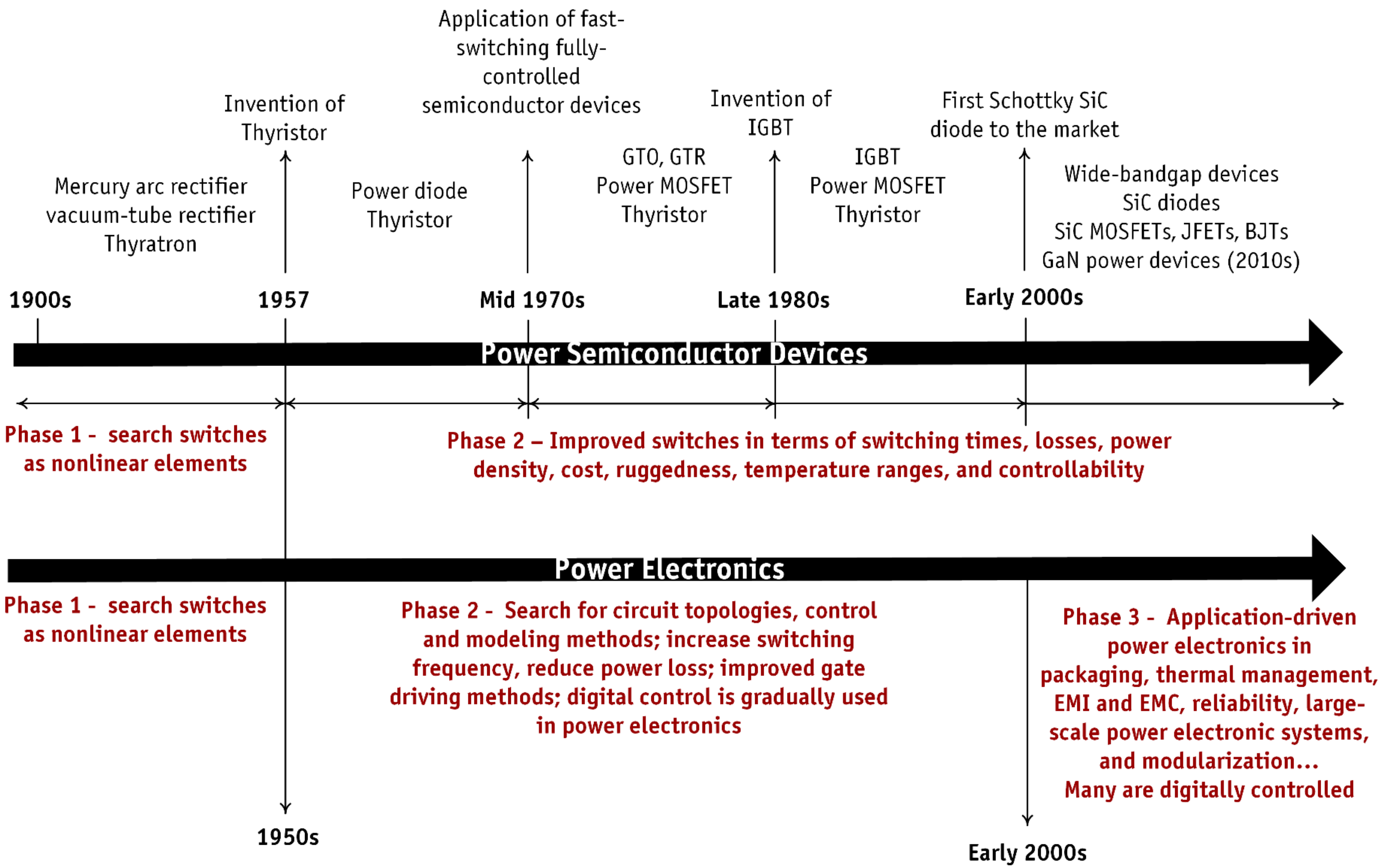
Power Electronics in all aspects of Energy



Energy

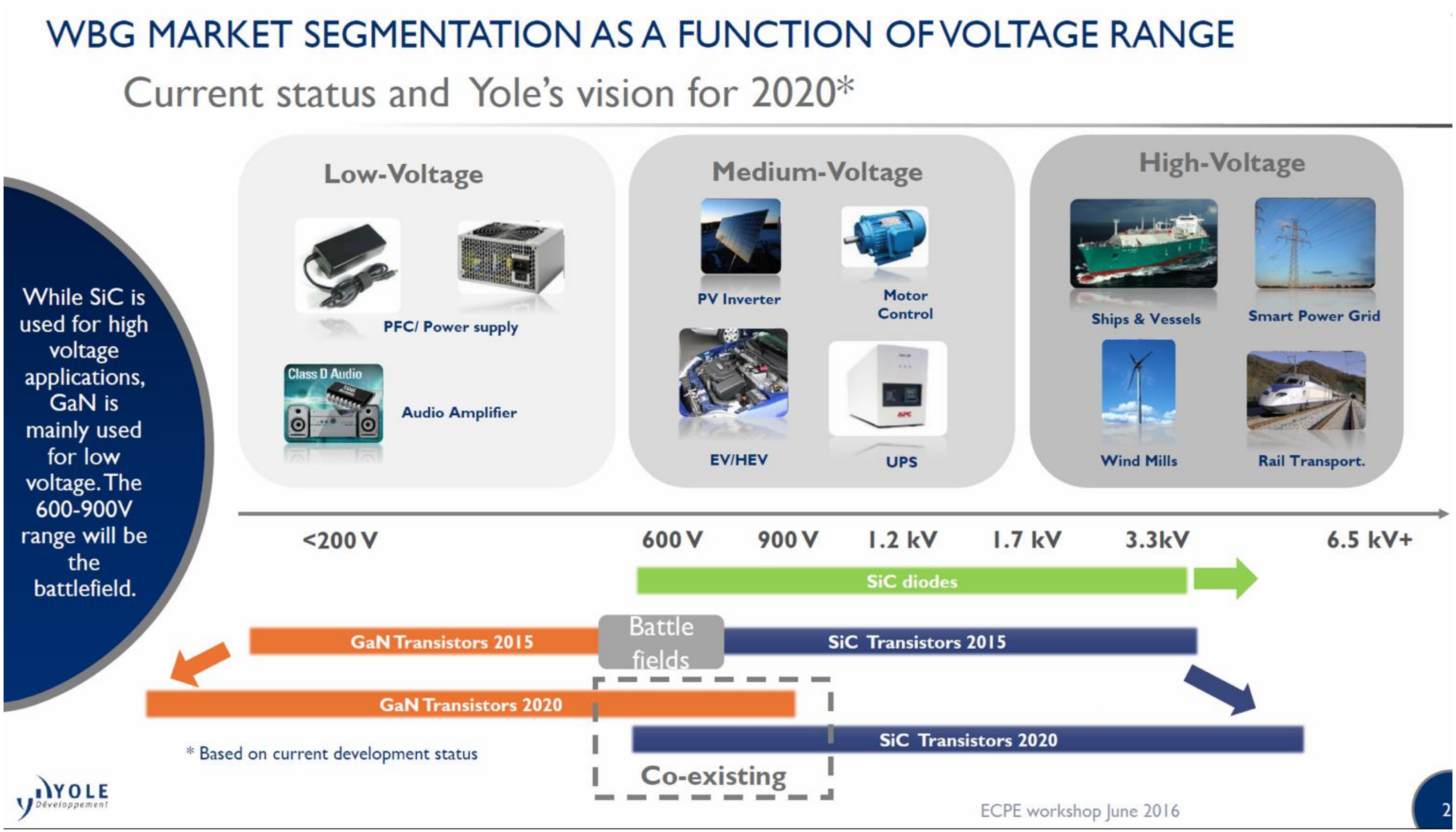
Production | Distribution | Consumption | Control

100+ Years of Power Electronics



Reliability becomes one of the key application-oriented challenges

Wide-bandgap Semiconductors: Application ranges



Sources

Yole Developpement, ECPE Workshop 2016

G. Meneghesso, "Parasitic and Reliability issues in GaN-Based Transistors", CORPE Workshop 2018, Aalborg, Denmark

Wide-bandgap Semiconductors

	Si	GaAs	4H-SiC	6H SiC	GaN/ AlGaN
Band gap energy E_g (eV)	1.1 ind.	1.43 dir.	3.26 ind.	3.0 ind.	3.42 dir.
Electron mobility μ_e (cm^2/Vs)	1500	8500	1000	500	1300 >2000 (2DEG)
Electric breakdown field E_{crit} (10^6 V/cm)	0.3	0.4	2.0	2.4	3.3
Saturation velocity v_{sat} (10^7 cm/s)	1.0	2.0	2.0	2.0	2.7
Thermal conductivity κ (W/Kcm)	1.5	0.46	4.9	4.9	2.4
Johnsons Figure of Merit ($\sim V_{Br}^2 \times v_{sat}^2$)	1	7	180	260	760
Maximum operation temperature T_{max} (°C)	200	300	500	500	500

…. but fully usable only if heat dissipation can be managed

→ trade-off

Physical parameters of common wide-bandgap semiconductors in comparison with Silicon

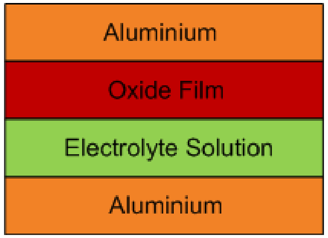
Sources

Joachim Würfl, "GaN Power Devices (HEMT): Basics, Advantages and Perspectives", ECPE Workshop 2013

G. Meneghesso, "Parasitic and Reliability issues in GaN-Based Transistors", CORPE Workshop 2018, Aalborg, Denmark

Typical Capacitors in Power Electronic Applications

Sandwich
(Source: http://www.jhdeli.com/Templates/Cold_Sandwich.html)



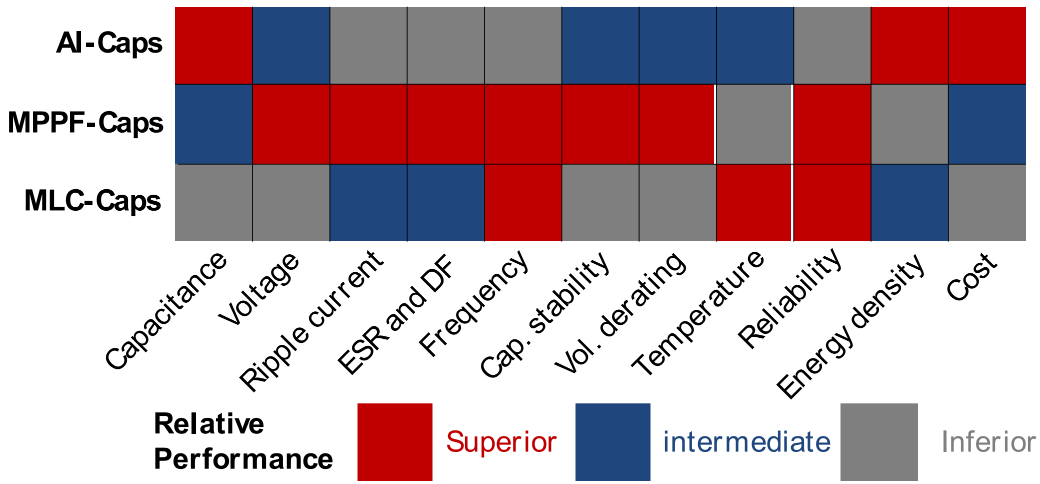
Aluminum Electrolytic Capacitor

Capacitance

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

Ripple current rating

$$I_r = \sqrt{\frac{P_d}{R_s}} = \sqrt{\frac{hA\Delta T}{R_s}}$$



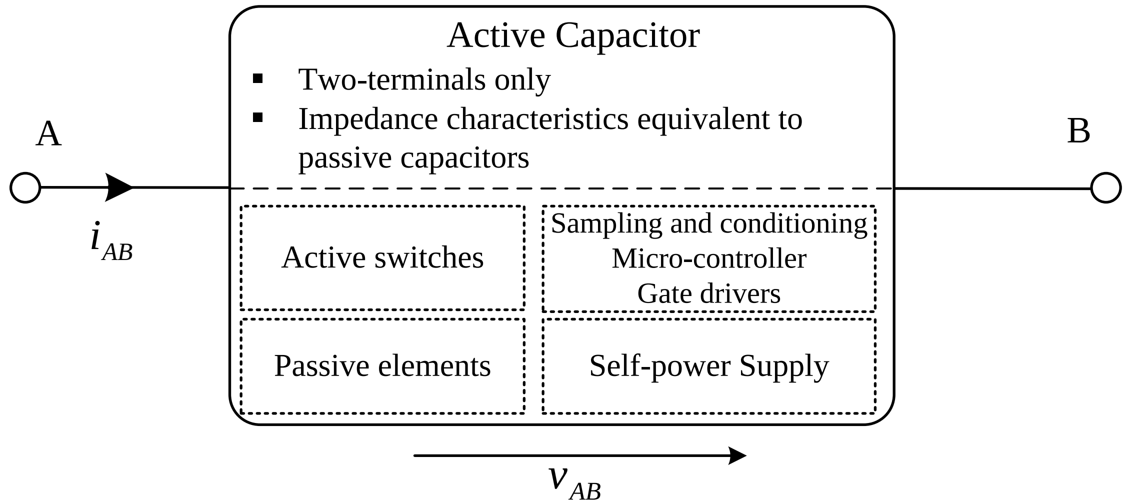
Al-Caps Aluminum Electrolytic Capacitors
MPPF-Caps Metallized Polypropylene Film Capacitors
MLC-Caps Multilayer Ceramic Capacitors

Capacitors might be a bottleneck in modern power electronics

Concept of a Two-terminal Active Capacitor

Feature

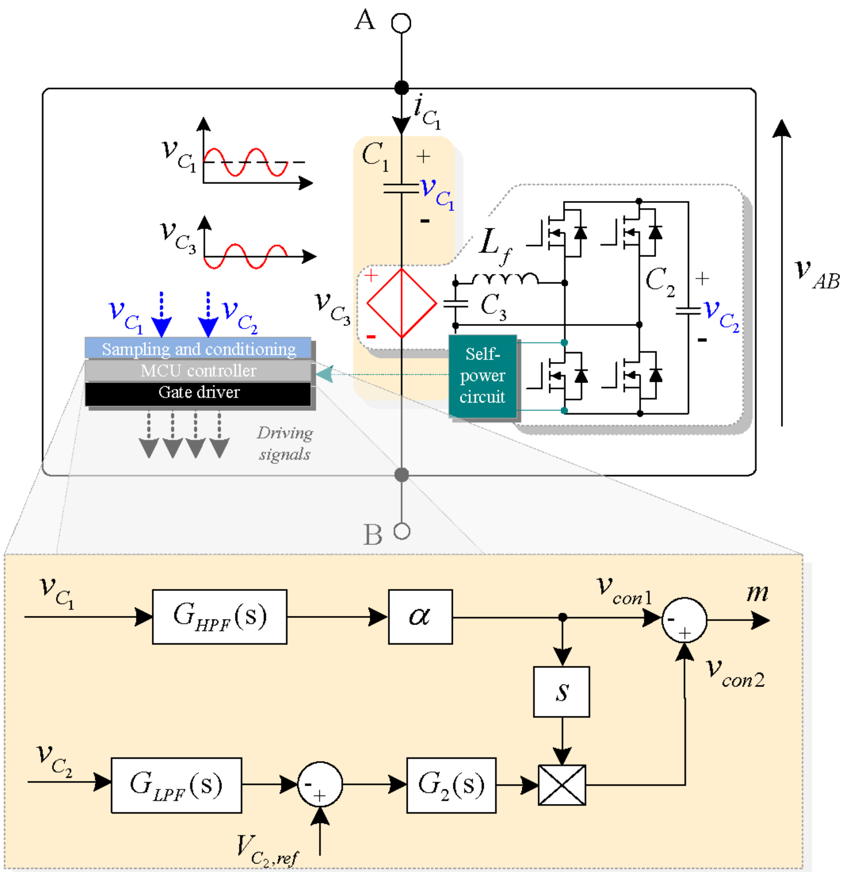
- ❑ No signal connection to main circuit
- ❑ No auxiliary power supply
- ❑ Only two-terminal ”A” and ”B” connected to external main circuit



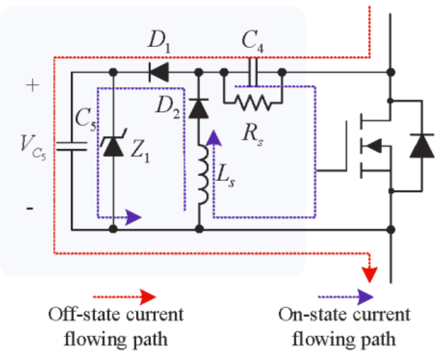
- ❑ Retain the same level of convenience as a conventional passive capacitor
- ❑ Application independent
- ❑ Lowest apparent power processed by the auxiliary circuit

Source: H. Wang, H. Wang and F. Blaabjerg, ¨ A two-terminal active capacitor device ¨

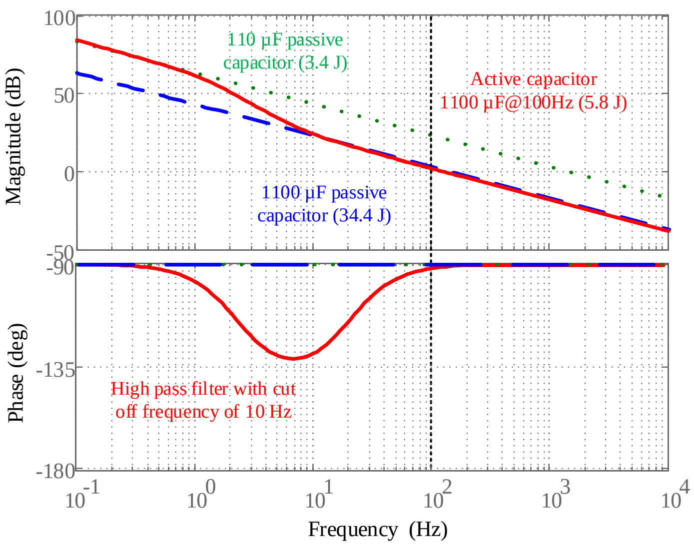
Proof-of-Concept of a Two-terminal Active Capacitor



An implementation of the two-terminal active capacitor concept



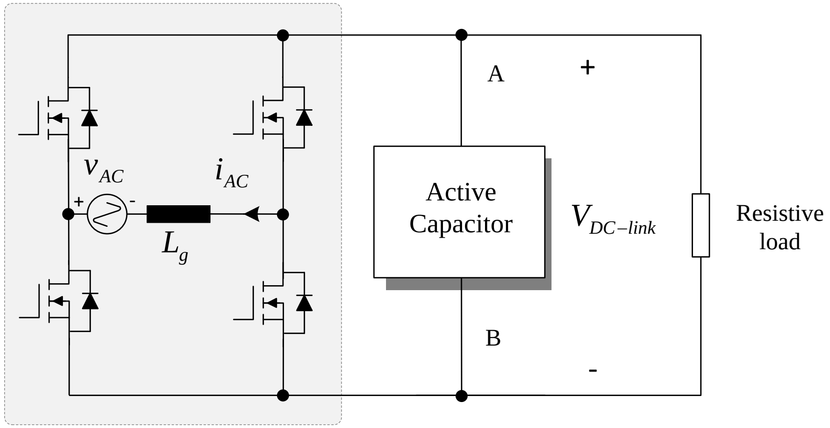
Internal auxiliary power from MOSFET



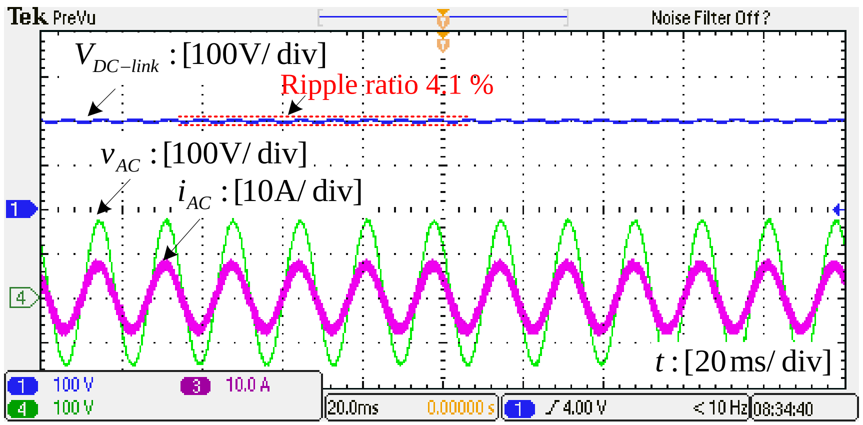
Impedance characteristics of active capacitor

Source: Haoran Wang and Huai Wang, "A two-terminal active capacitor," IEEE Transactions on Power Electronics, 2017

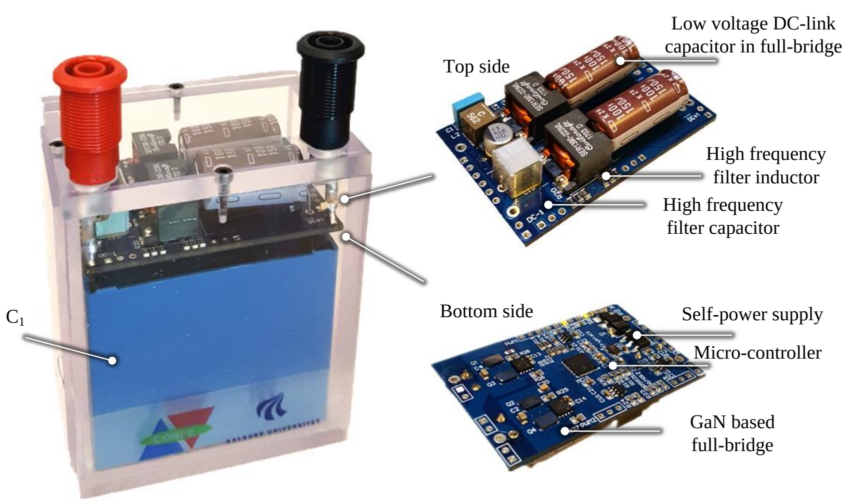
Experimental Results of Active Capacitor

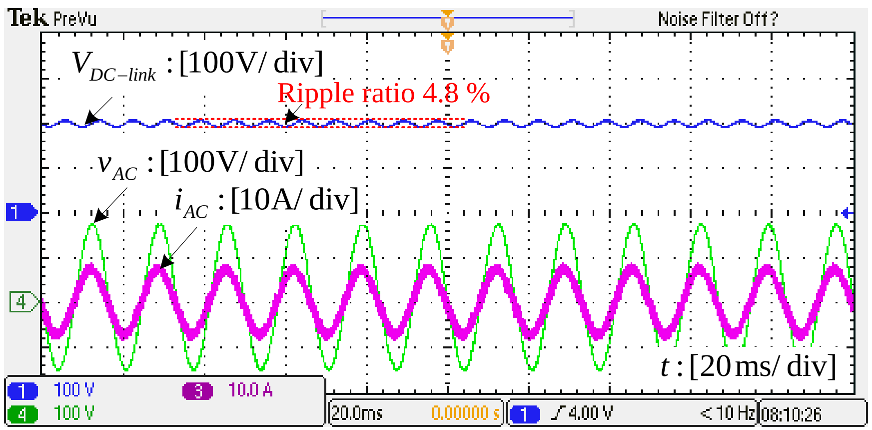


Single-phase system with active capacitor



Key waveforms of the system with 110uF active capacitor

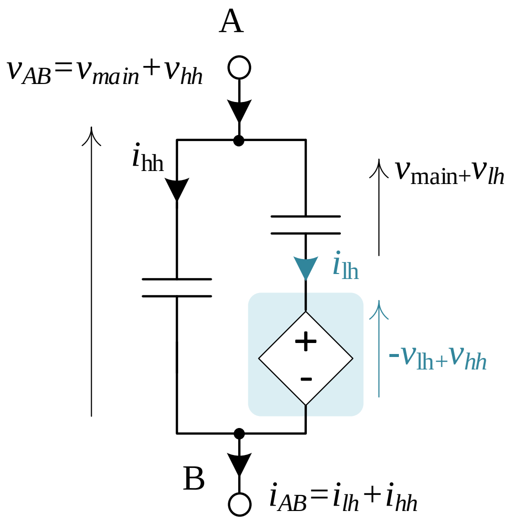




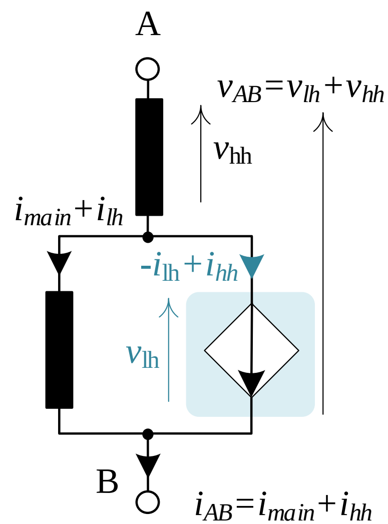
Key waveforms of the system with 1100uF passive capacitor

Duality of Active Capacitor and Inductor

Two-terminal active capacitor



Two-terminal active inductor



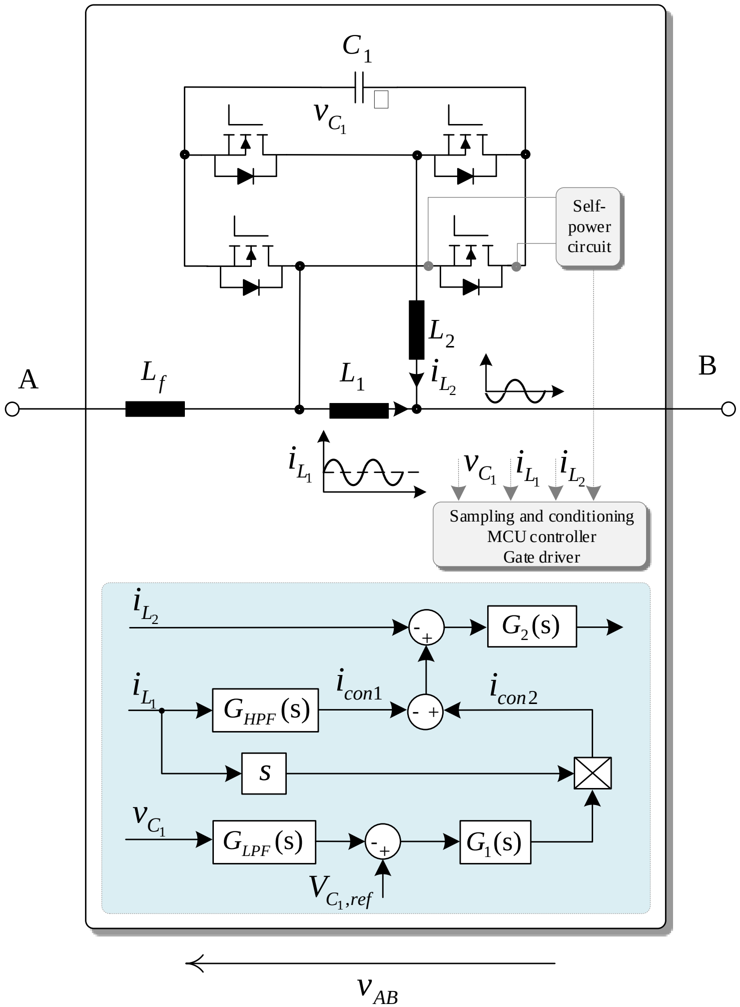
Minimum apparent power $\approx V_{lh} \times I_{lh}$

Features:

- it has two terminals only same as a conventional passive components without any external feedback signal and power supply, and
- the auxiliary circuit processes the minimum apparent power, which is the theoretical minimum limit.

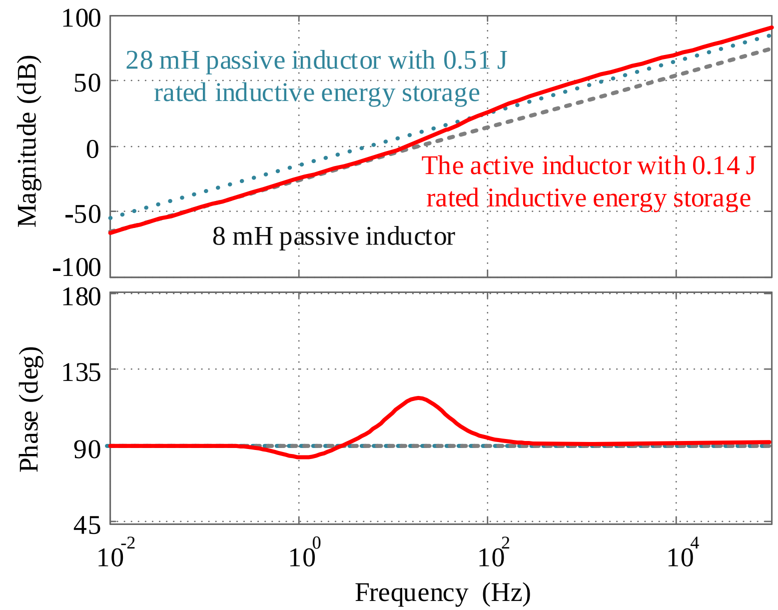
Source: H. Wang and H. Wang, " A two-terminal active inductor device "

Circuit Diagram of Active Inductor Device



Features:

- Current control based on internal voltage and current information of the auxiliary circuit
- Same impedance with passive inductor in frequency of interest



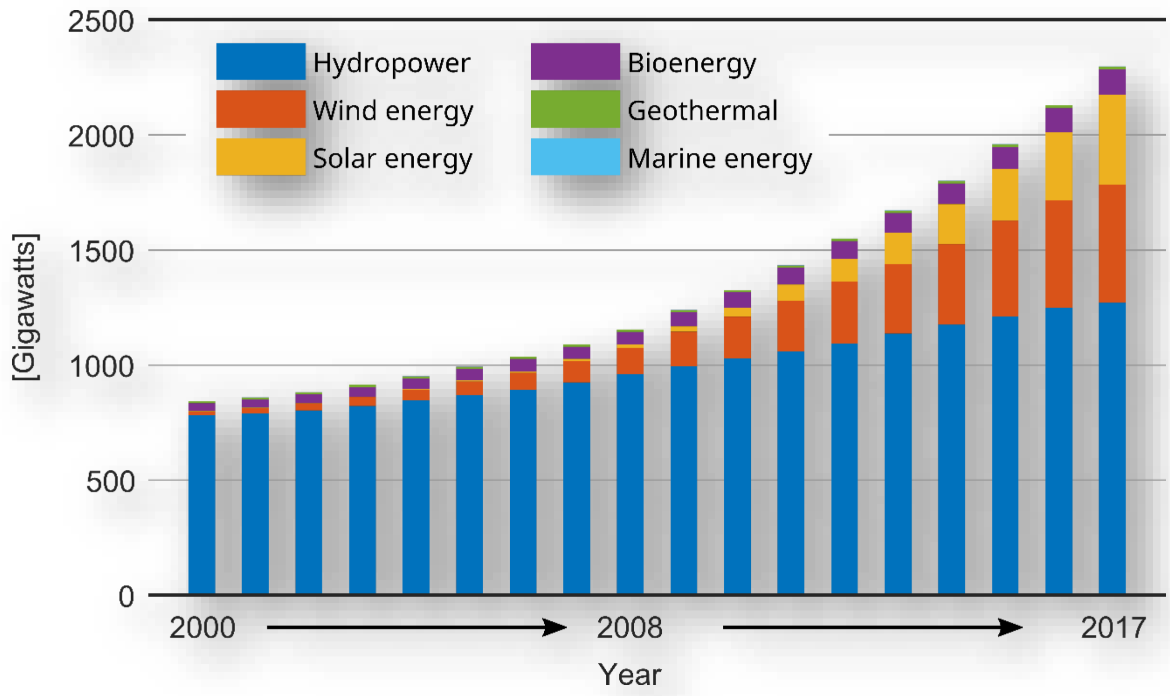
Source: Haoran Wang and Huai Wang, "A Two-terminal Active Inductor with Minimum Apparent Power for the Auxiliary Circuit," IEEE Transactions on Power Electronics, 2018

Power Electronics and Components – Quo Vadis

- Power Electronics devices driving the power electronics
- WBG on fast move – Silicon still a player.. – base material critical
- Reliability needs to be more proven for WBG
- New packaging technique developed
- Lower volume, higher power density, more critical
- Radical change in equipment design – x10 in switching frequency
- New skills are needed – eg from antenna domain
- 3D/4D/5D/6D design methods are necessary
- Technology will develop fast – lack of models
- Passive components can be a bottle-neck
- Active passive components give flexibility
- Curriculums have to be updated

Renewable Energy Systems

State of the Art – Renewable Evolution

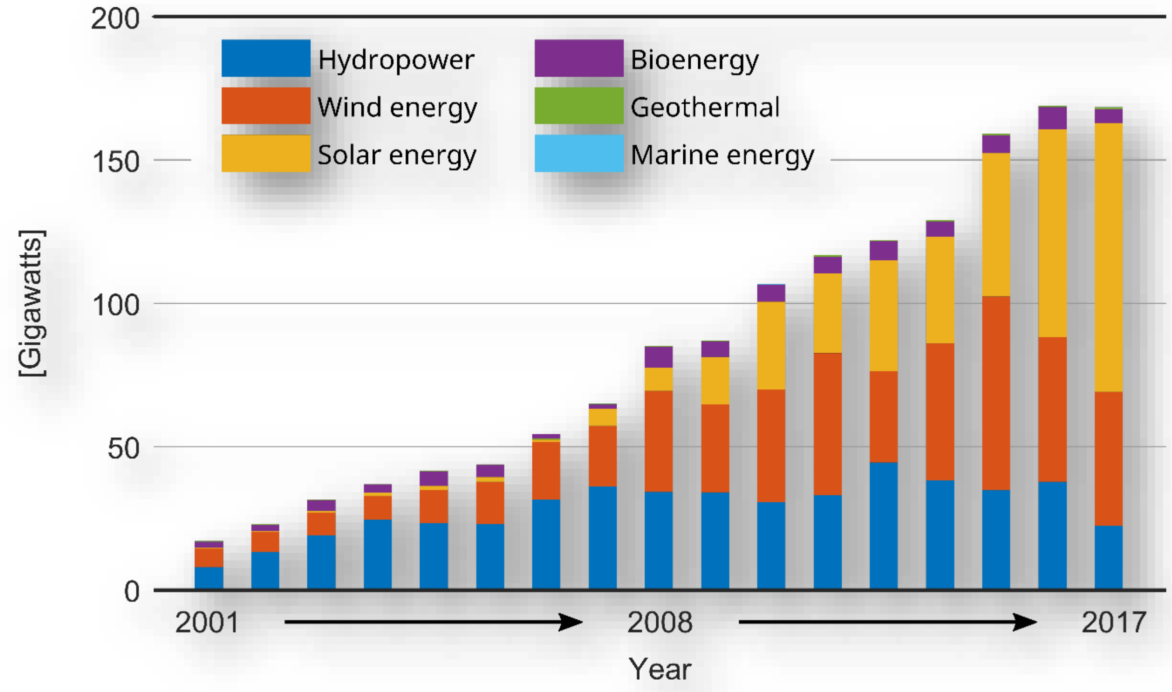


Worldwide Installed Renewable Energy Capacity (2000-2017)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy

(Source: IRENA, “Renewable energy capacity statistics 2018”, http://www.irena.org/publications, March 2018)

Global RES Annual Changes

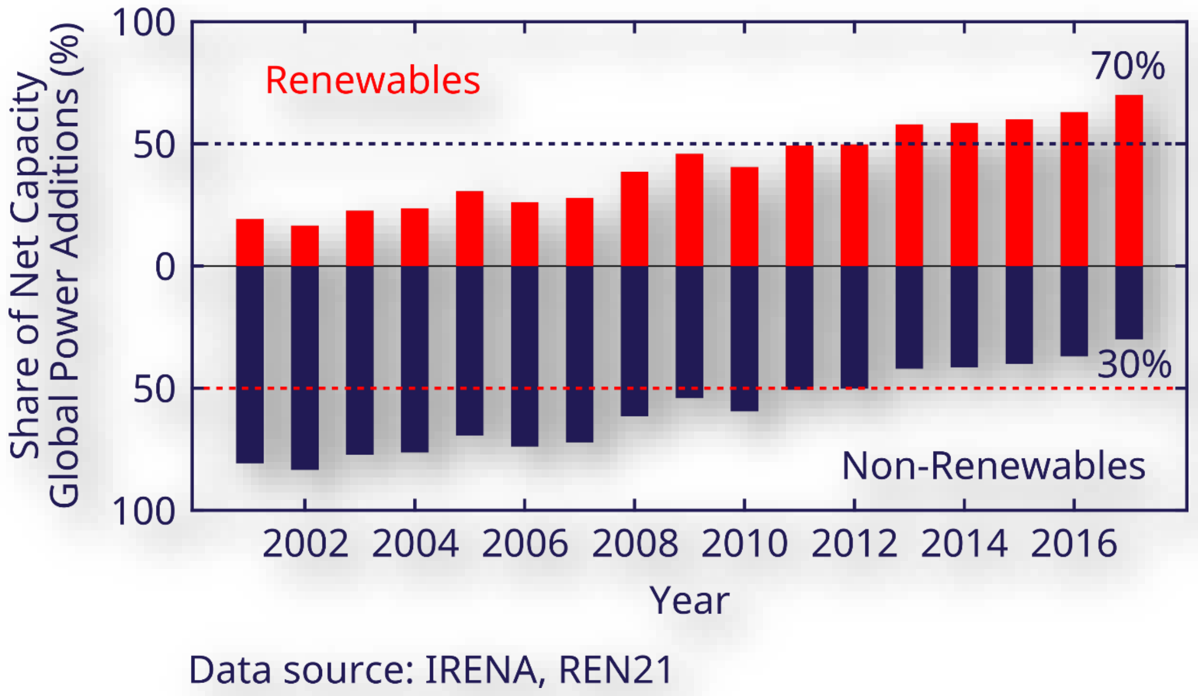


Global Renewable Energy Annual Changes in Gigawatt (2001-2017)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy

(Source: IRENA, “Renewable energy capacity statistics 2018”, http://www.irena.org/publications, March 2018)

Share of the Net Total Annual Additions

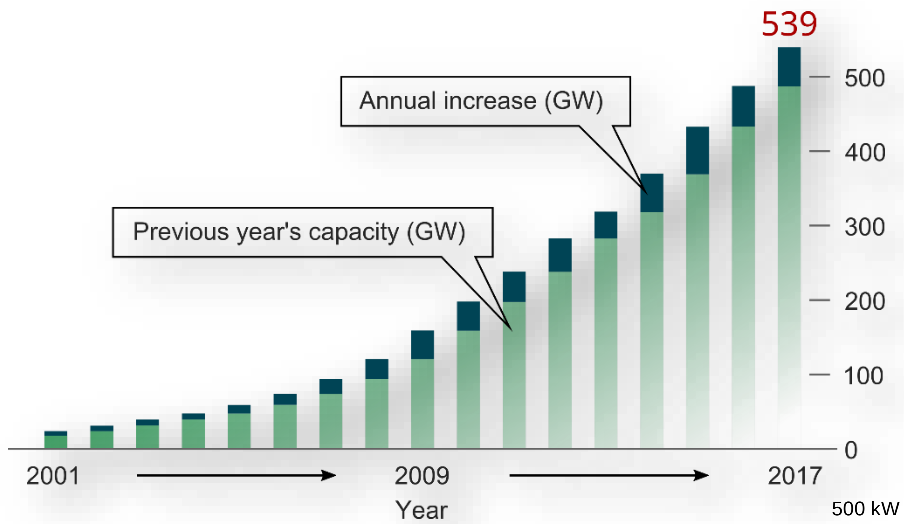


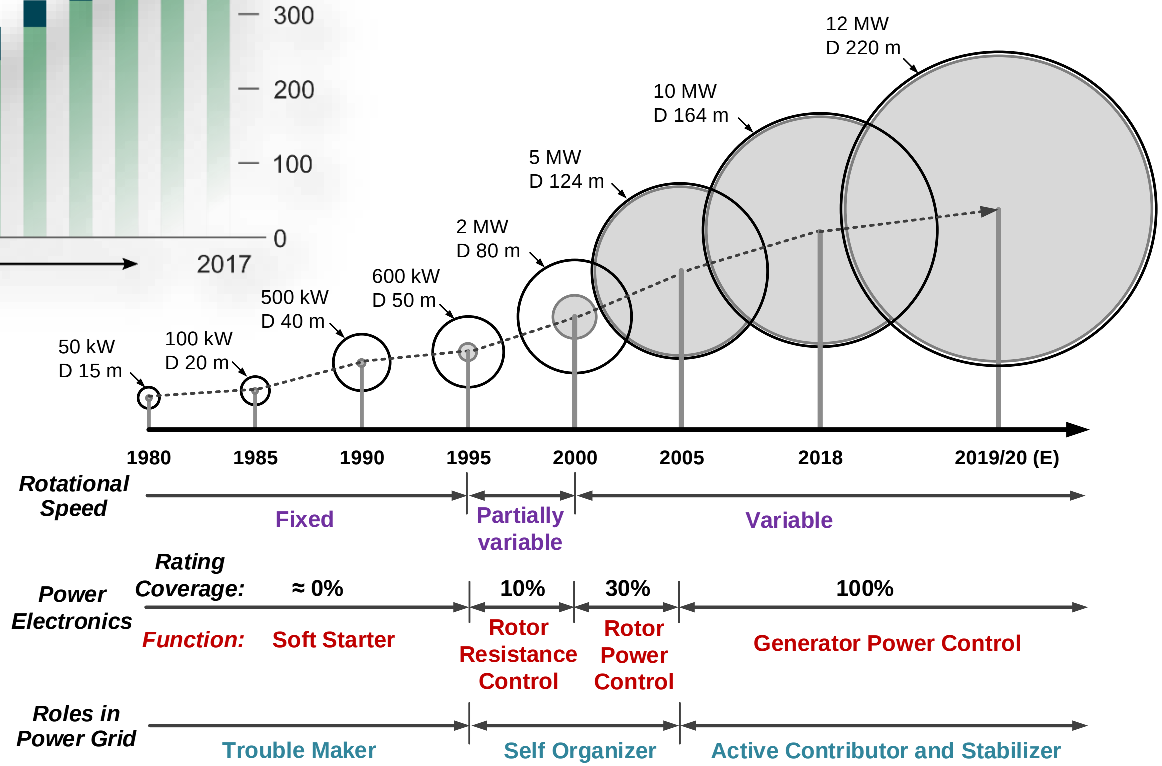
RES and non-RES as a share of the net total annual additions

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

State of the Art Development – Wind Power





Global installed wind capacity (until 2017): 539 GW, 2017: 52.3 GW

- Higher total capacity (+50% non-hydro renewables).
- Larger individual size (average 1.8 MW, up to 6-8 MW, even 12 MW).
- More power electronics involved (up to 100 % rating coverage).

http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf

Top 5 Wind Turbine Manufacturers & Technologies

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

DFIG: Doubly-Fed Induction Generator

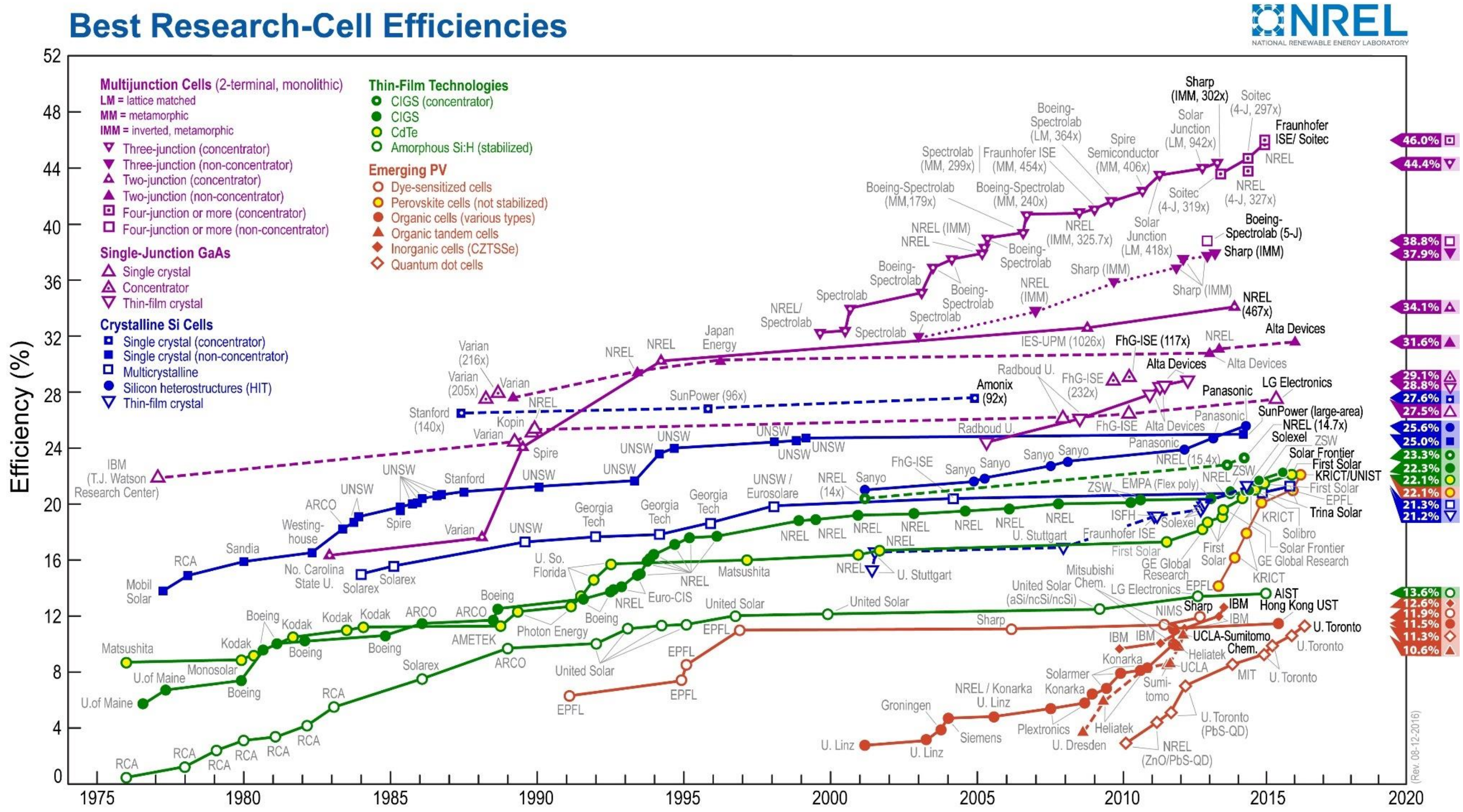
PMSG: Permanent Magnet Synchronous Generator

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/

State of the Art – PV Cell Technologies



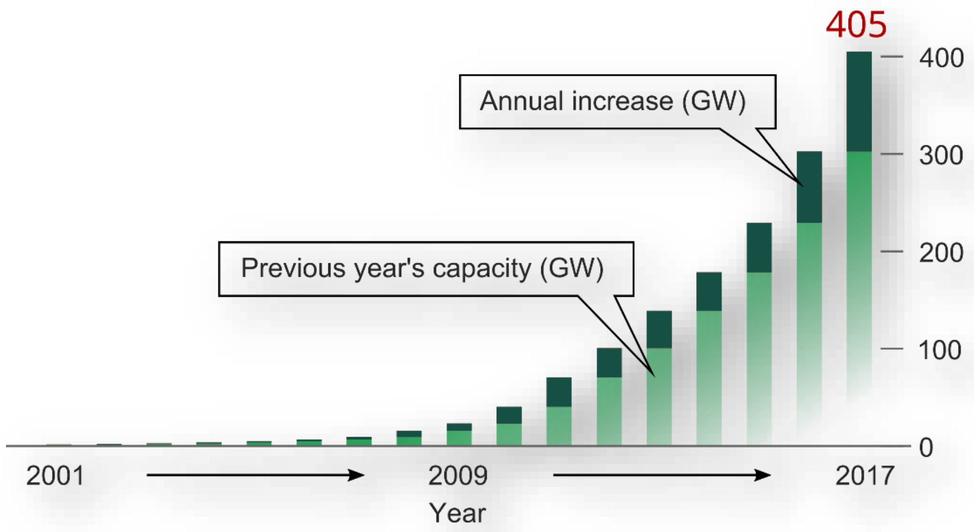
National Renewable Energy Laboratory, http://www.nrel.gov/pv/assets/images/efficiency_chart.jpg

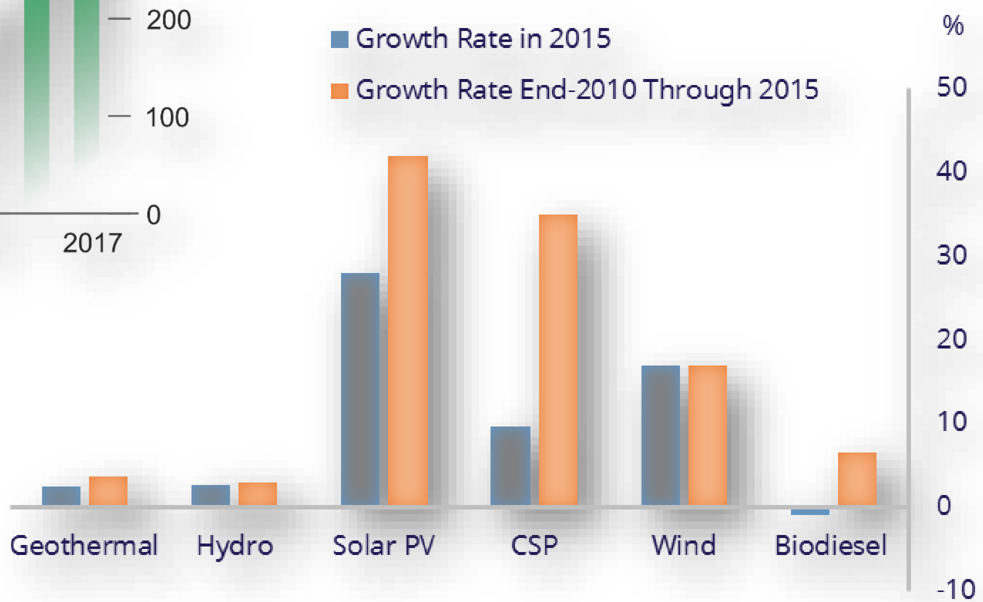
Top 10 Solar PV Manufacturers to Watch in 2018

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/

State of the Art Development – Photovoltaic Power



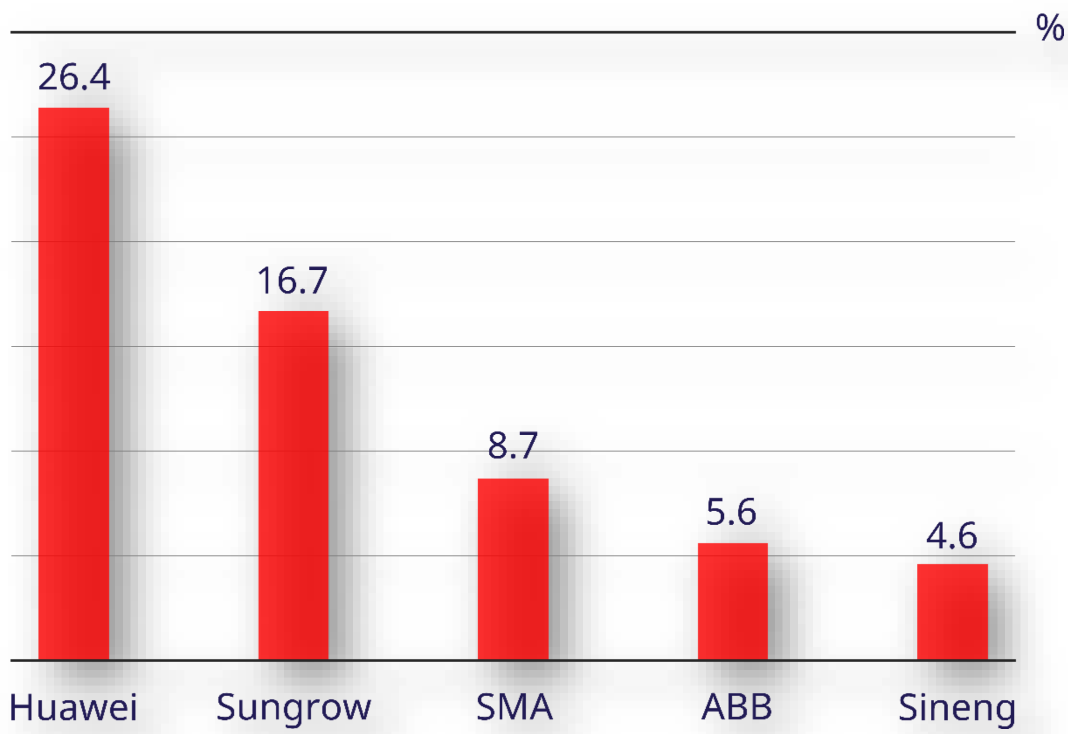


Global installed solar PV capacity (until 2017): 405 GW, 2017: 102 GW

- 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

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

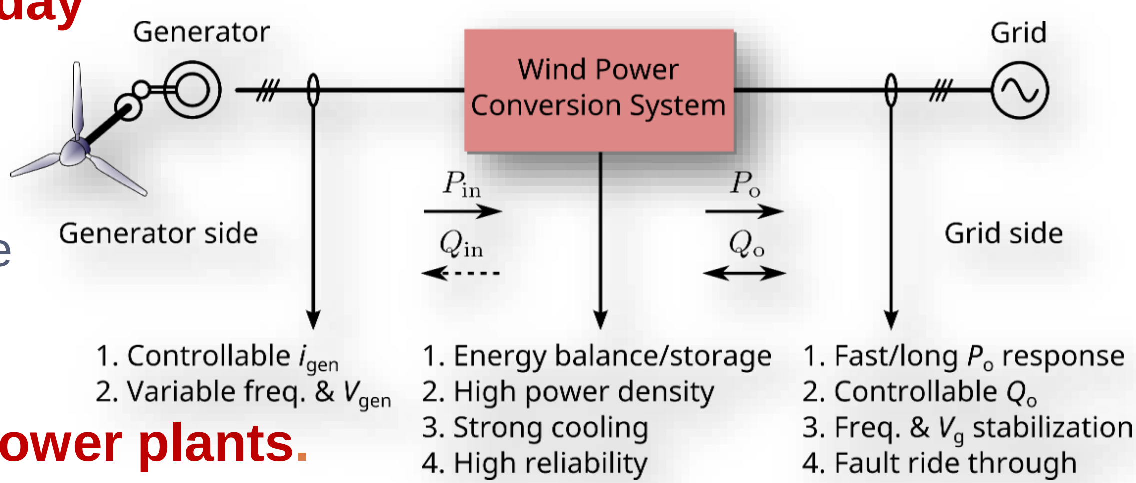
Grid Codes for Wind Turbines

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



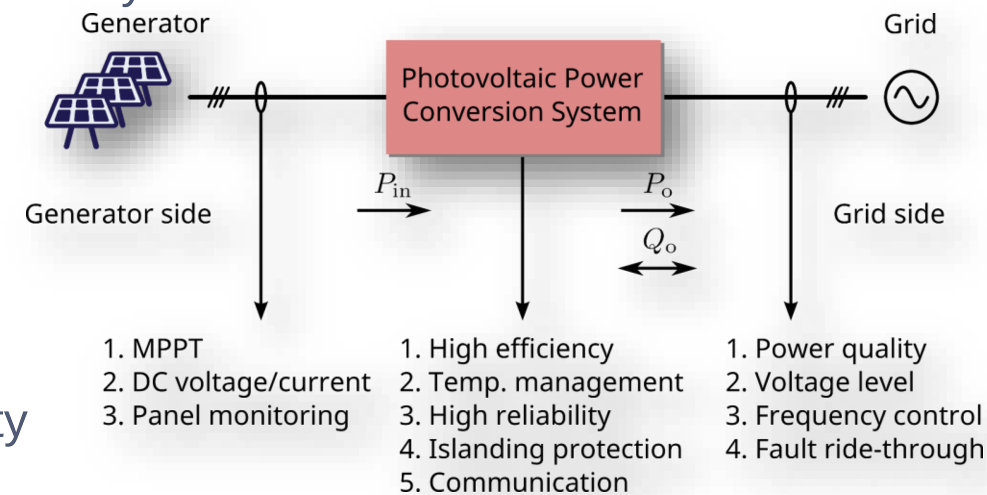
Wind turbines are active power plants.

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

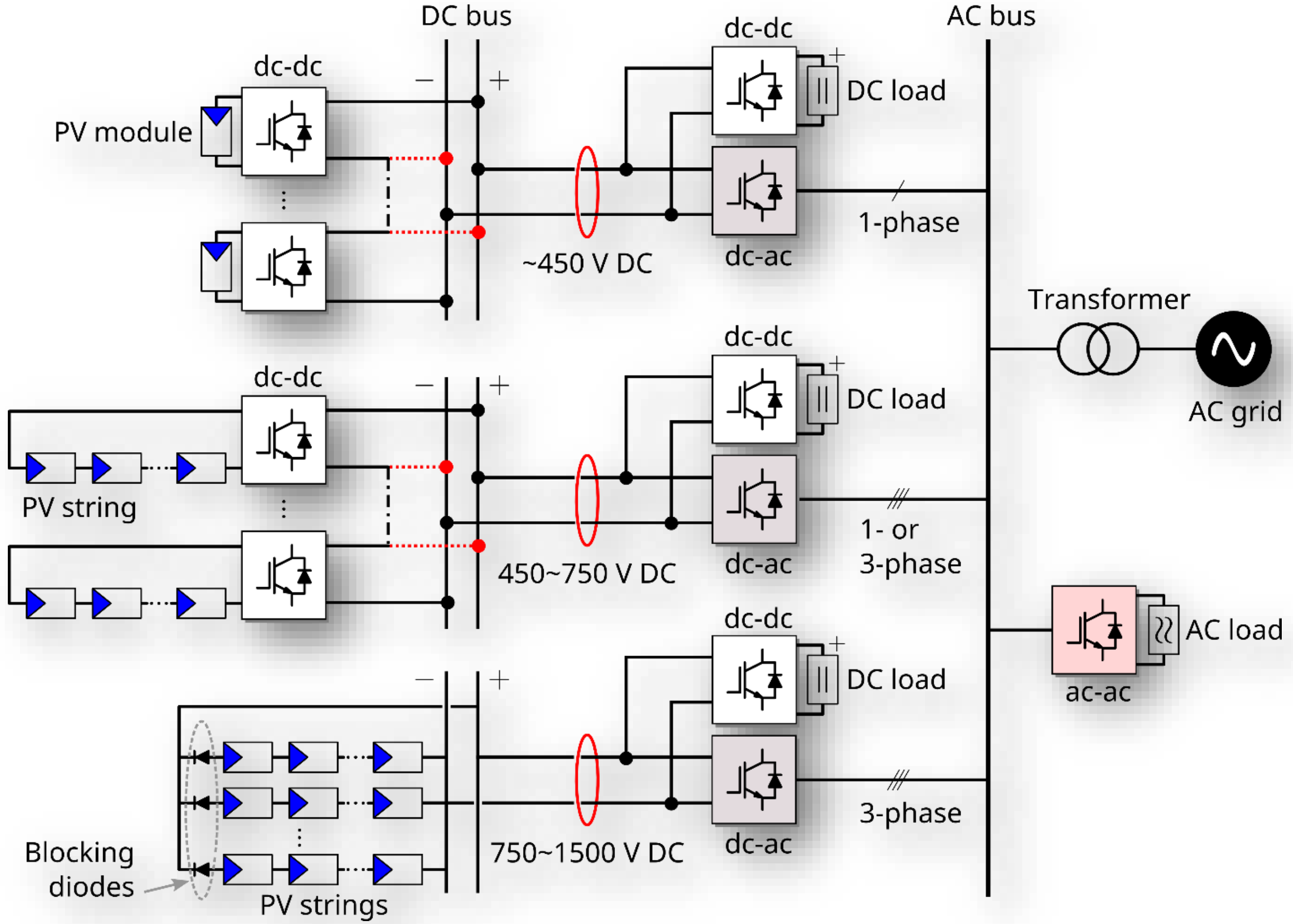
- Maximize active power capture (MPPT)
- Power quality issue
- Anti Islanding
- Ancillary services for grid stability
- Communications
- High efficiency



Large-scale system

- Frequency control
- Virtual Inertia
- Fault ride-through capability
- …

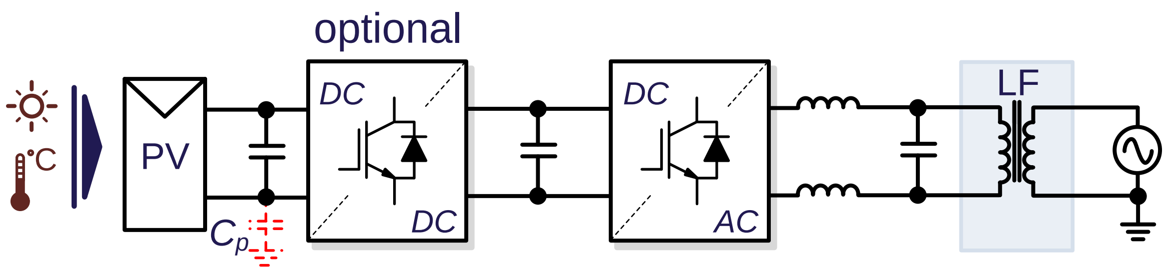
PV Inverter System Configurations

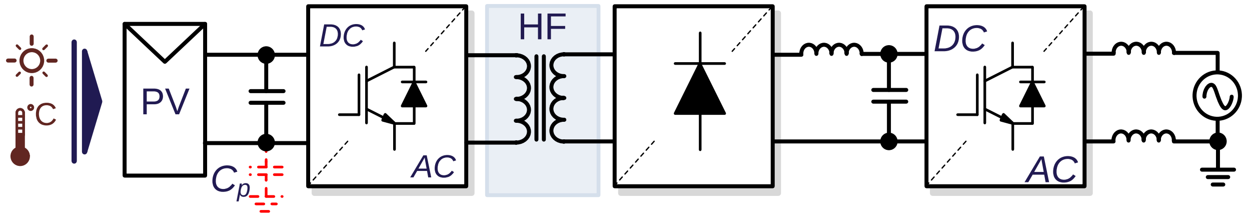


Module Converters | String Inverter | Multi-String Inverters | Central Inverters

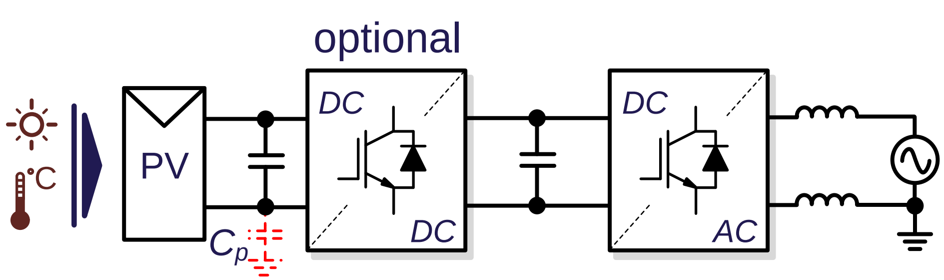
Grid-Connection Configurations

Transformer-based grid-connection



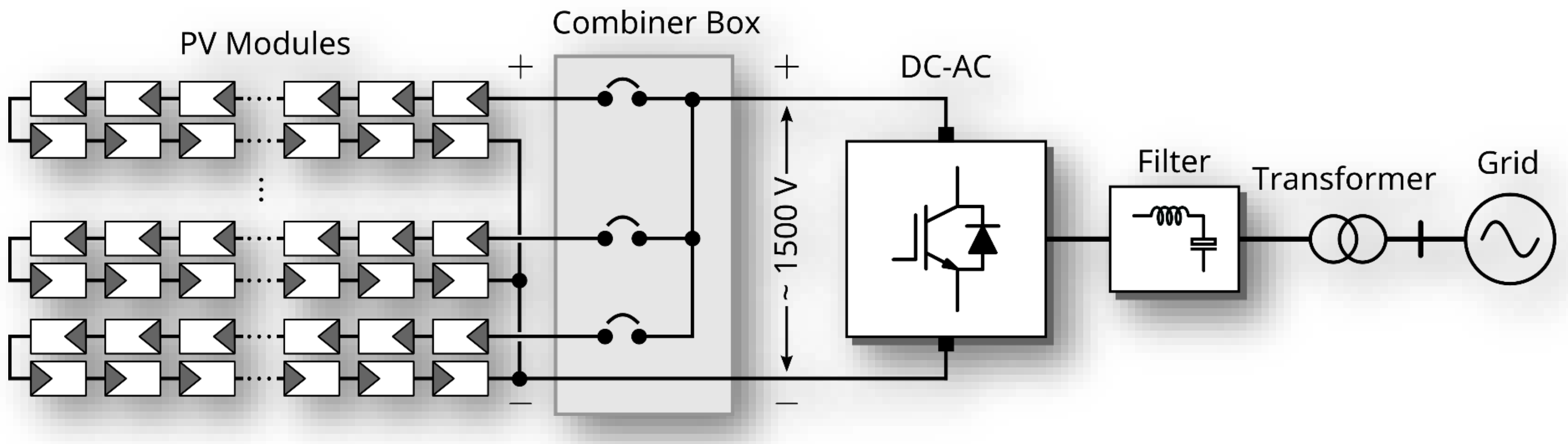


Transformerless grid-connection → Higher efficiency, Smaller volume



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

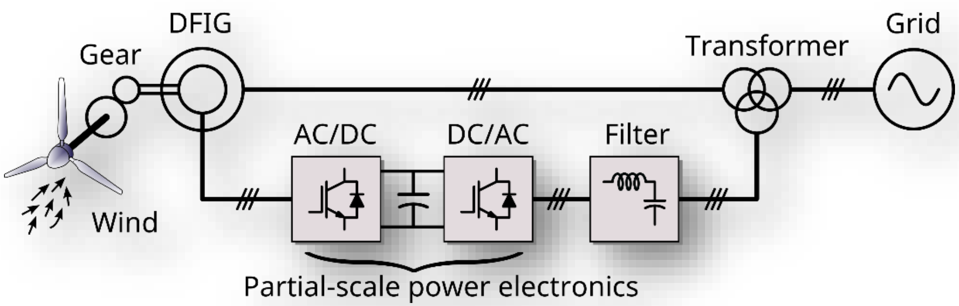
Becoming the mainstream solution!

ABB MW Solution

Sungrow five-level topology

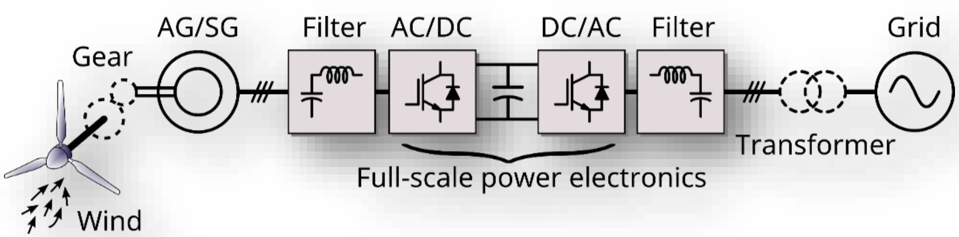
https://www.pv-tech.org/products/abb-launches-high-power-1500-vdc-central-inverter-for-harsh-conditions
https://www.pv-tech.org/products/sungrows-1500vdc-sg125hv-string-inverter-enables-5mw-pv-power-block-designs

Wind turbine concept and configurations



Partial scale converter with DFIG

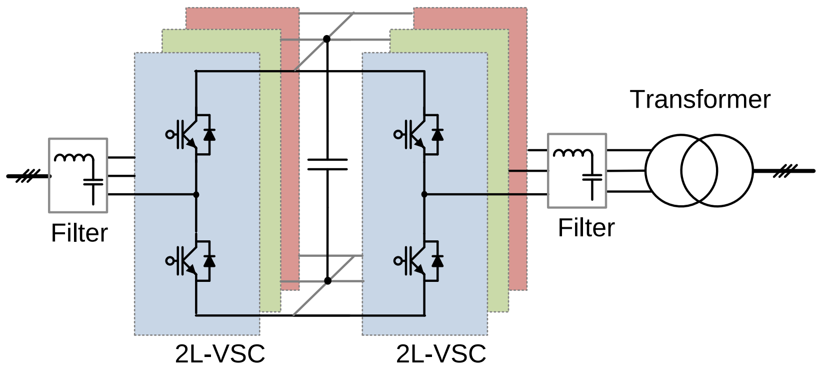
- Variable pitch – variable speed
- Doubly Fed Induction Generator
- Gear box and slip rings
- ±30% slip variation around synchronous speed
- Power converter (back to back/ direct AC/AC) in rotor circuit
- ✓ State-of-the-art solutions



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

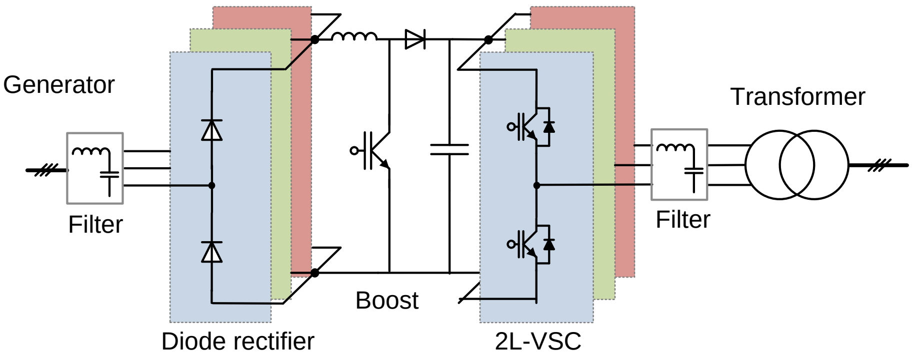
Converter topologies under low voltage (<690V)



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.

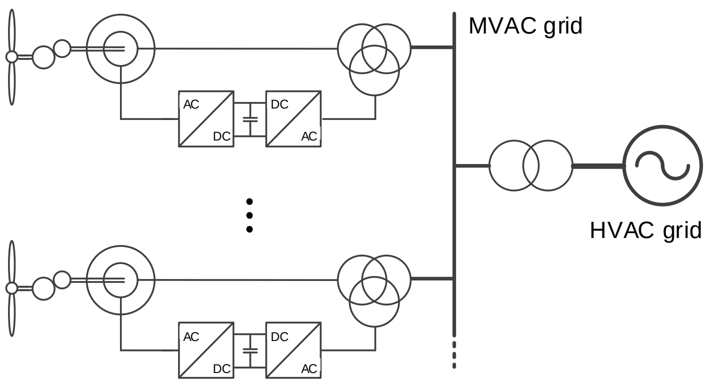
Medium voltage for large Wind Turbines seen

A 400 MW off-shore Wind Power System in Denmark

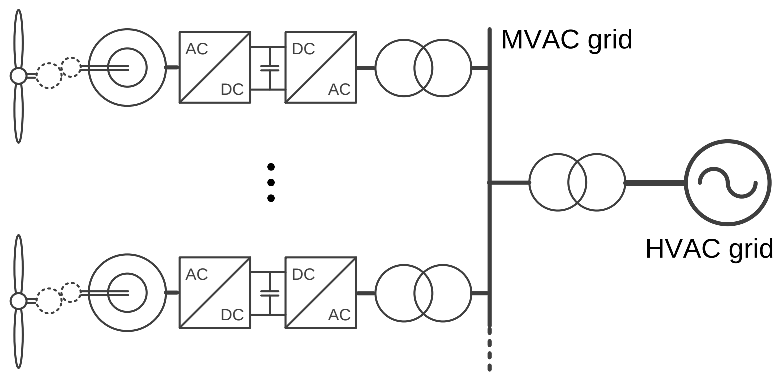
Anholt-DK (2016) – Ørsted

Wind Farm with AC and DC Power Transmission

HVAC power transmission

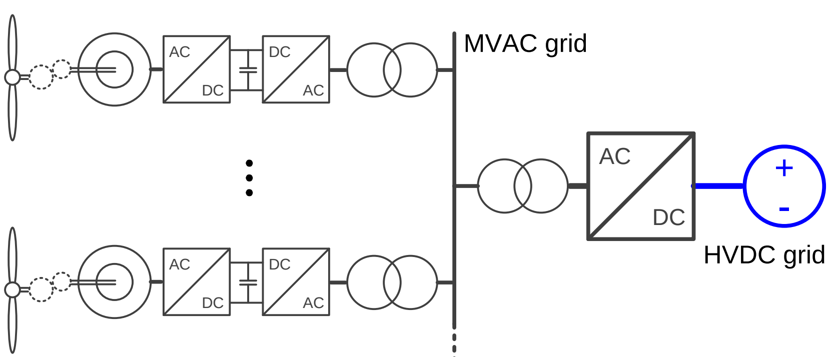


Partial-scale converter system

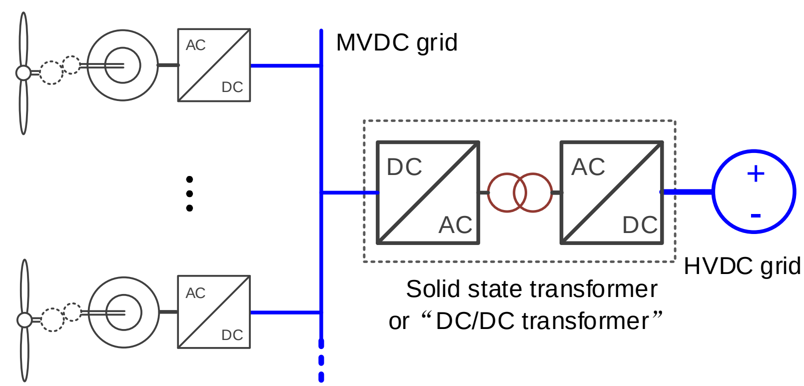


Full-scale converter system

HVDC power transmission

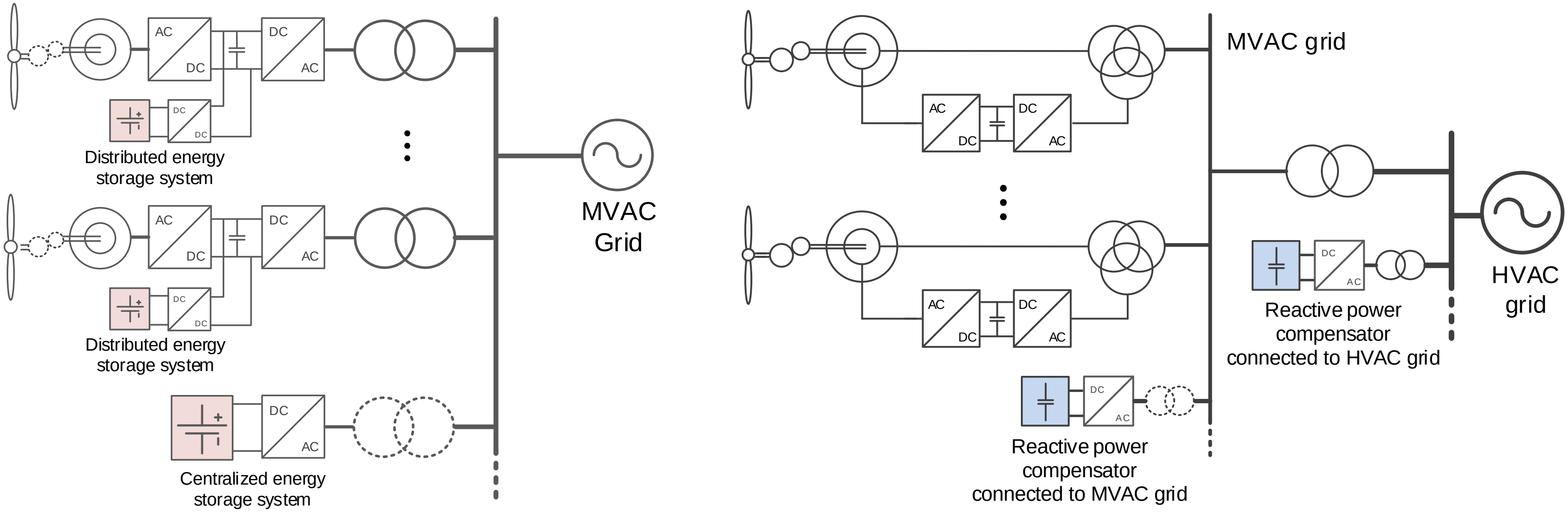


DC transmission grid



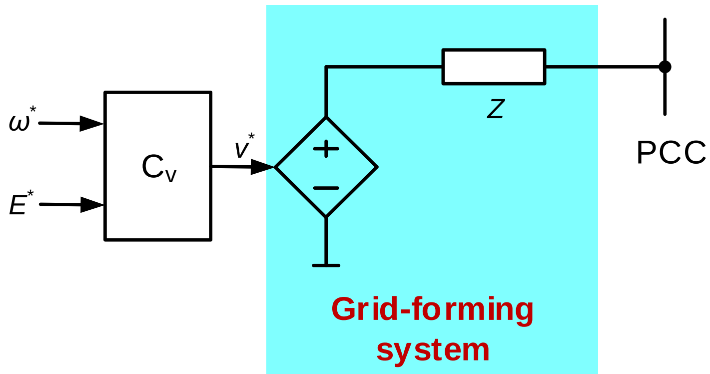
DC distribution & transmission grid

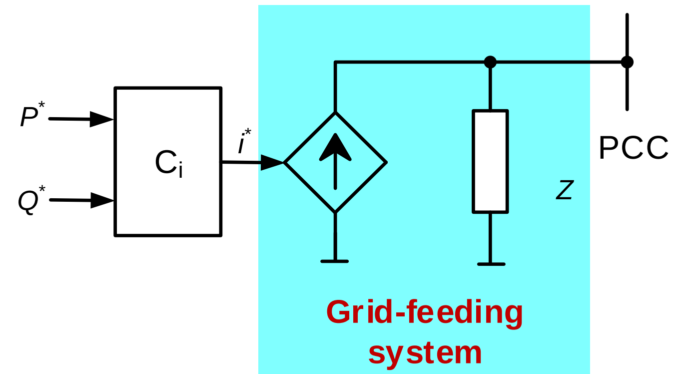
Active/Reactive Power Regulation in Wind Farm

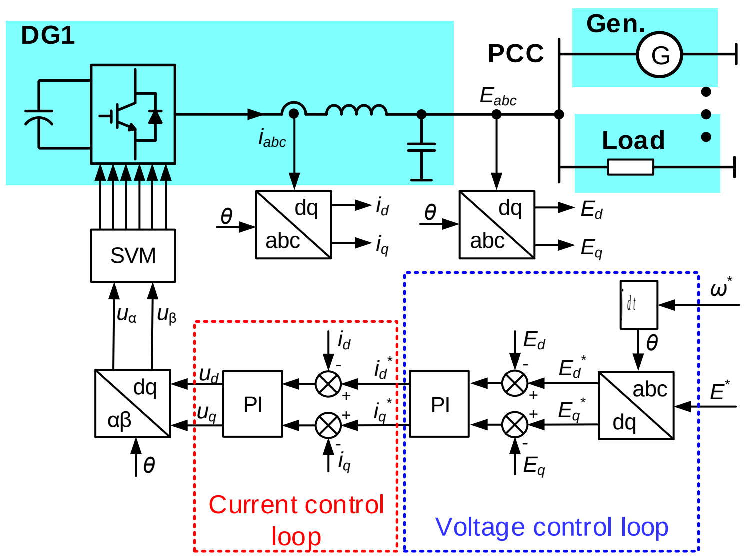


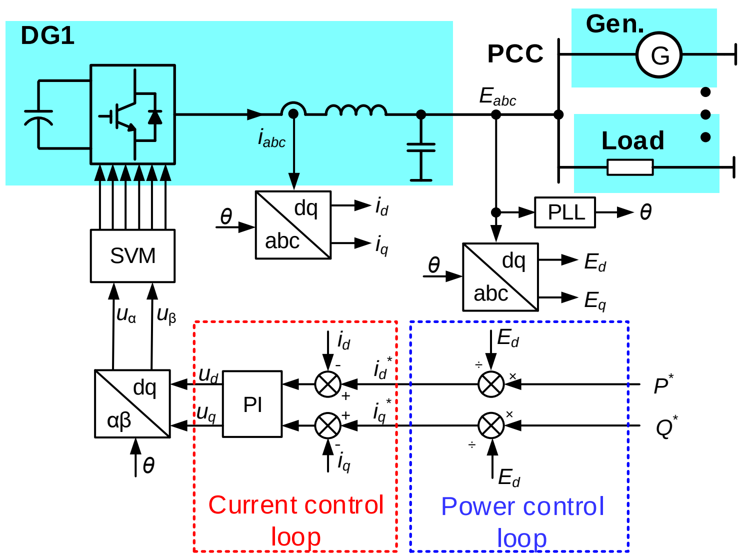
- ❖ Advanced grid support feature achieved by power converters and controls
- ❖ Local/Central storage system by batteries/supercapacitors
- ❖ Reactive power compensators
  - STATCOMs/SVCs
  - Medium-voltage distribution grid/High-voltage transmission grid

Grid-forming & Grid-feeding Systems (examples)





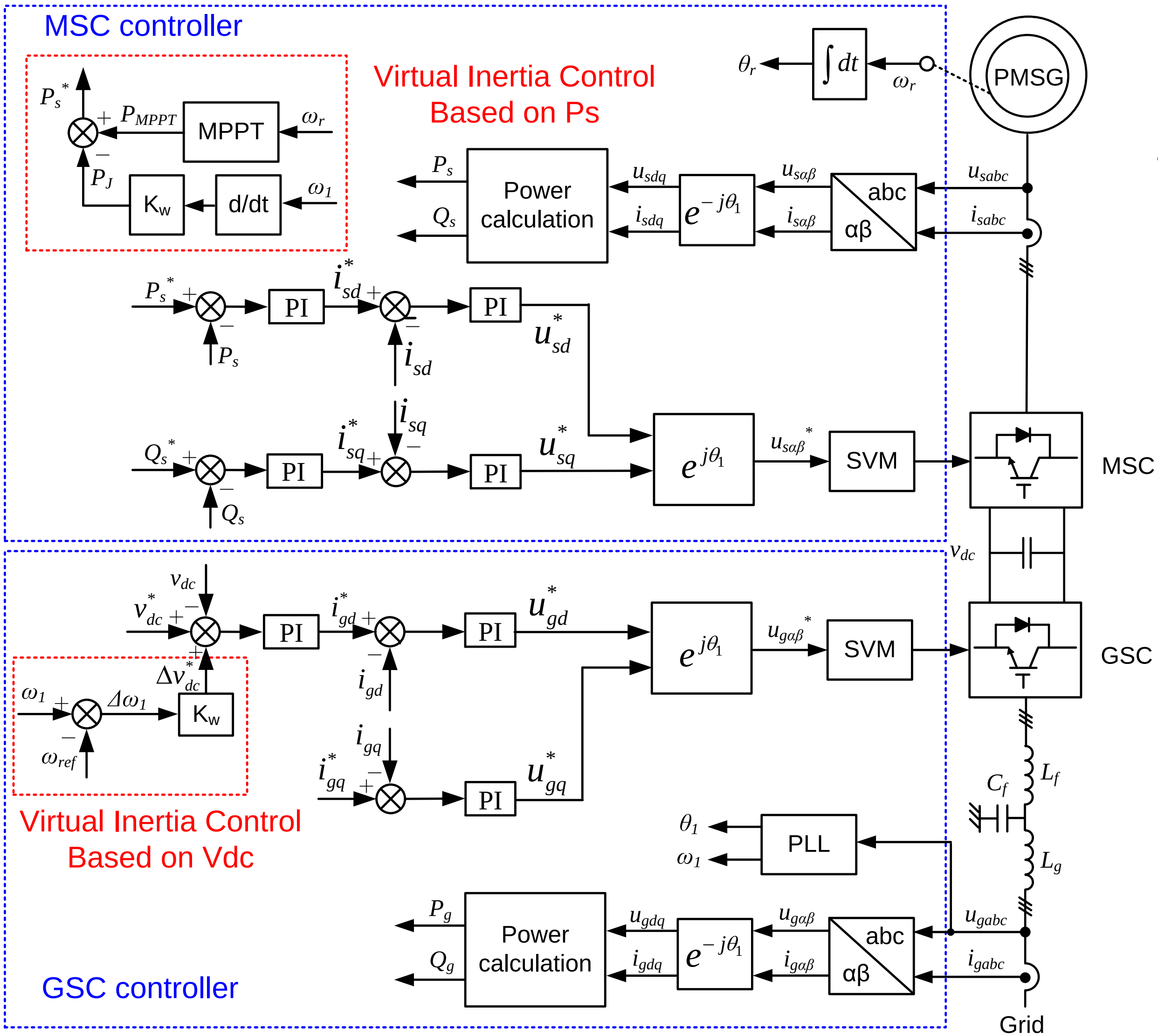




- Voltage-source based inverter
- Control reference: voltage amp. & freq.

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

Virtual Inertia Emulation in PMSG based Wind System



Two virtual inertia solutions:

1) Virtual inertia control based on Ps in MSC controller;

2) Virtual inertia control based on Vdc in GSC controller;

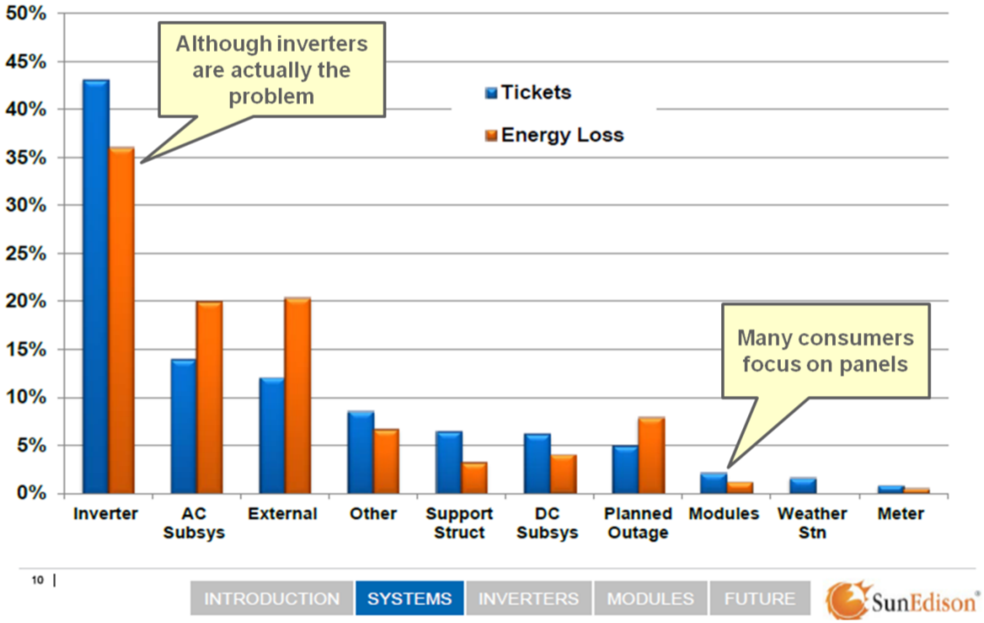
Renewable energy systems – Quo Vadis

- 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 constantly change – improve technology
- More intelligence into the control of renewables
- Grid-feeding/Grid forming – how to do in large scale systems ?
- Storage is coming into system solutions
- Black start of systems (Inrush currents – how to do it)
- Protection coordination in future grid ?
- Stability of PE-Dominated grid
- Other energy carriers will be a part of large scale system balance
- Renewables 100 % competitive in 10 Years………. Power electronics is enabling

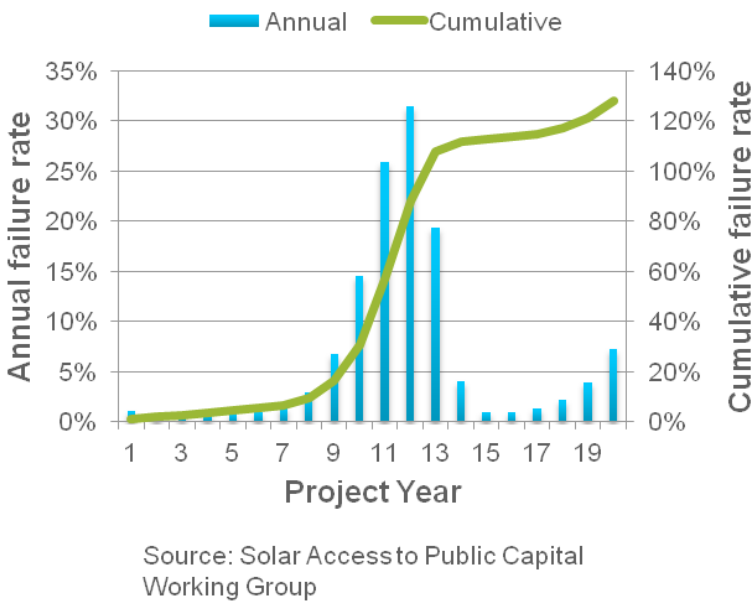
Reliable Power Electronics

Field Experience Examples 1/2

Failure frequency of different components in PV systems



Failure frequency and energy impact



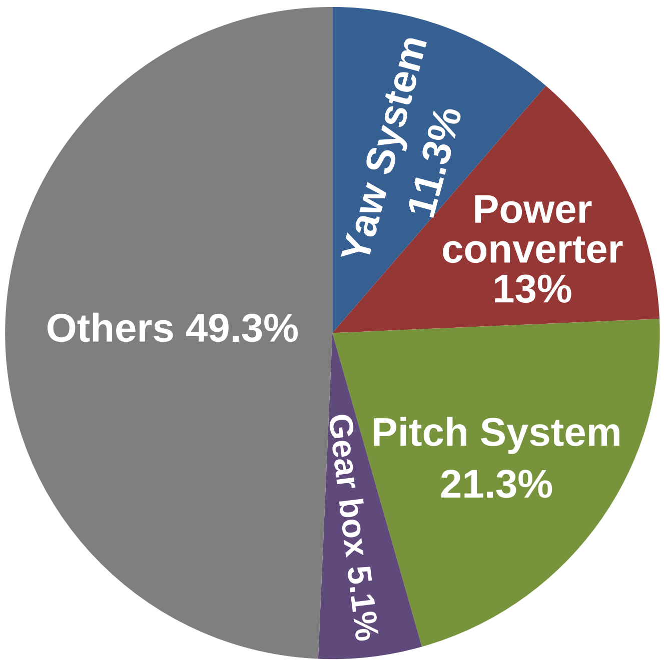
Example of failure rate of PV inverter (string inverter) in field operation

Data source: PV System Reliability—An owner's perspective" SunEdison 2012

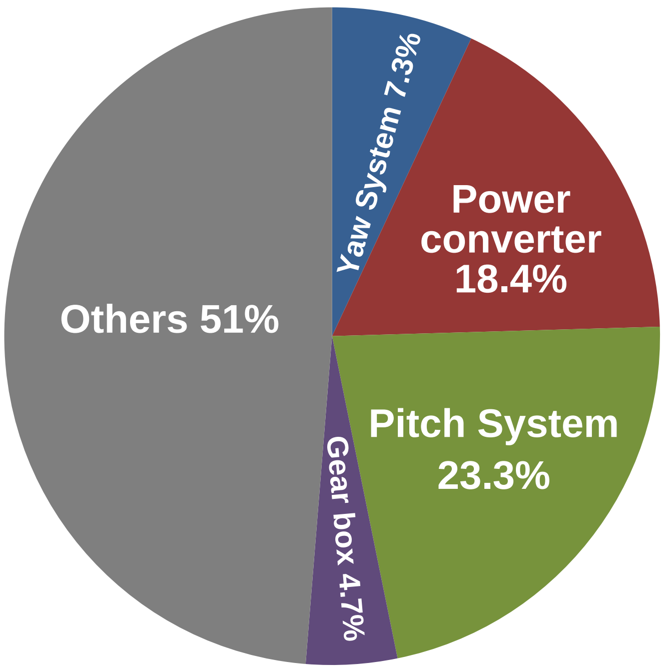
Data source: Greentech Media Webinar "How to Reduce Risk in Commercial Solar," July 2015

Field Experience Examples 2/2

350 onshore wind turbines in varying length of time (35,000 downtime events)



Contribution of subsystems and assemblies to the overall failure rate of wind turbines.



Contribution of subsystems and assemblies to the overall downtime of wind turbines.

Data source: Reliawind, Report on Wind Turbine Reliability Profiles – Field Data Reliability Analysis, 2011.

Availability Impact on Cost-of-Energy (COE)

$$COE = \frac{CAPEX + OPEX}{AEP}$$

CAPEX – Capital cost
OPEX – Operation and maintenance cost
AEP – Annual energy production

Higher reliability and better maintenance

↓

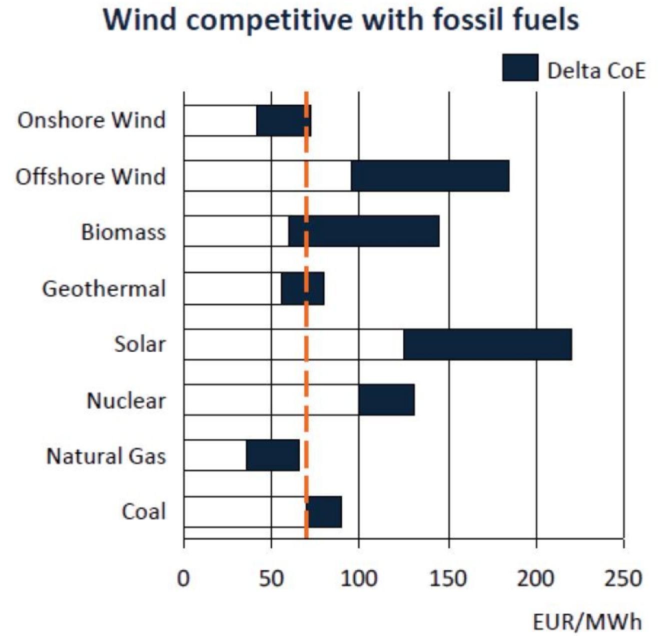
Lower downtime

↓

Lower OPEX and higher AEP

↓

Lower COE



Note: NG prices = USD 4.00-6.75/MMBTU, Coal = USD 1.60-1.70.MMBTU, onshore wind capacity factor = 30%, no CO2 costs for fossil technology, EUR = 1.45 USD.
Source, MAKE, Lazard,others

(source: MAKE Consulting A/S)

The Reliability Challenges in Industry

	Past	Present	Future
Customer expectations	✧ **Replacement if failure** ✧ **Years of warranty**	✧ **Low risk of failure** ✧ **Request for maintenance**	✧ **Peace of mind** ✧ **Predictive maintenance**
Reliability target	✧ **Affordable returns (%)**	✧ **Low return rates**	✧ **ppm return rates**
R&D approach	✧ **Reliability test** ✧ **Avoid catastrophes**	✧ **Robustness tests** ✧ **Improve weakest components**	✧ **Design for reliability** ✧ **Balance with field load**
R&D key tools	**Product operating tests**	✧ **Testing at the limits**	✧ **Understanding failure mechanisms, field load, root cause**, … ✧ **Multi-domain simulation** ✧ …

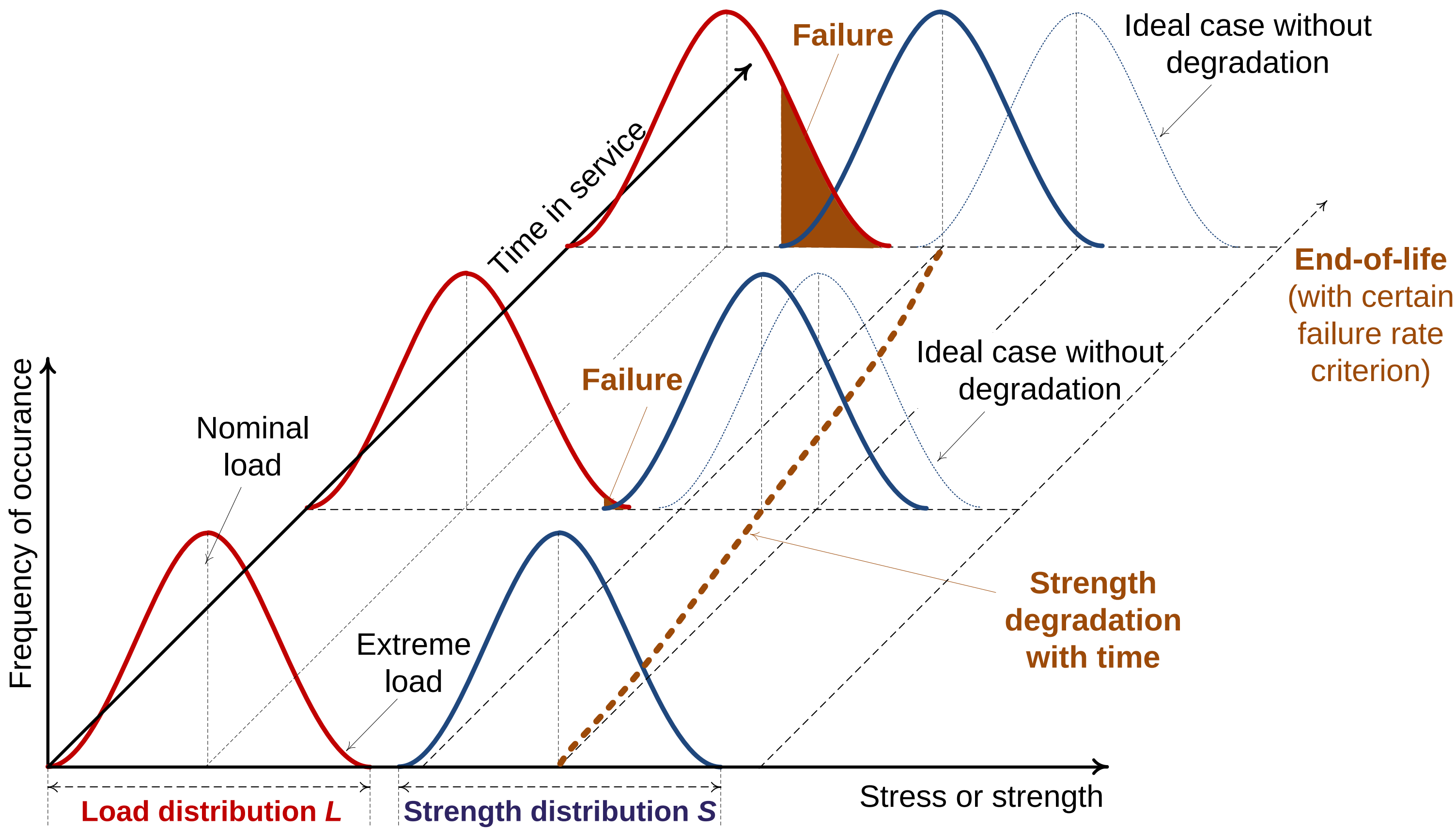
Reliability at CONSTRAINED cost is a challenge

Lifetime Targets in Power Electronics Intensive Applications

Applications	Typical design target of Lifetime
Aircraft	24 years (100,000 hours flight operation)
Automotive	15 years (10,000 operating hours, 300, 000 km)
Industry motor drives	5-20 years (60,000 hours in at full load)
Railway	20-30 years (73,000 hours to 110,000 hours)
Wind turbines	20 years (120,000 hours)
Photovoltaic plants	30 years (90,000 hours to 130,000 hours)

Stress-Strength Analysis

The essence of reliability engineering is to prevent the creation of failure



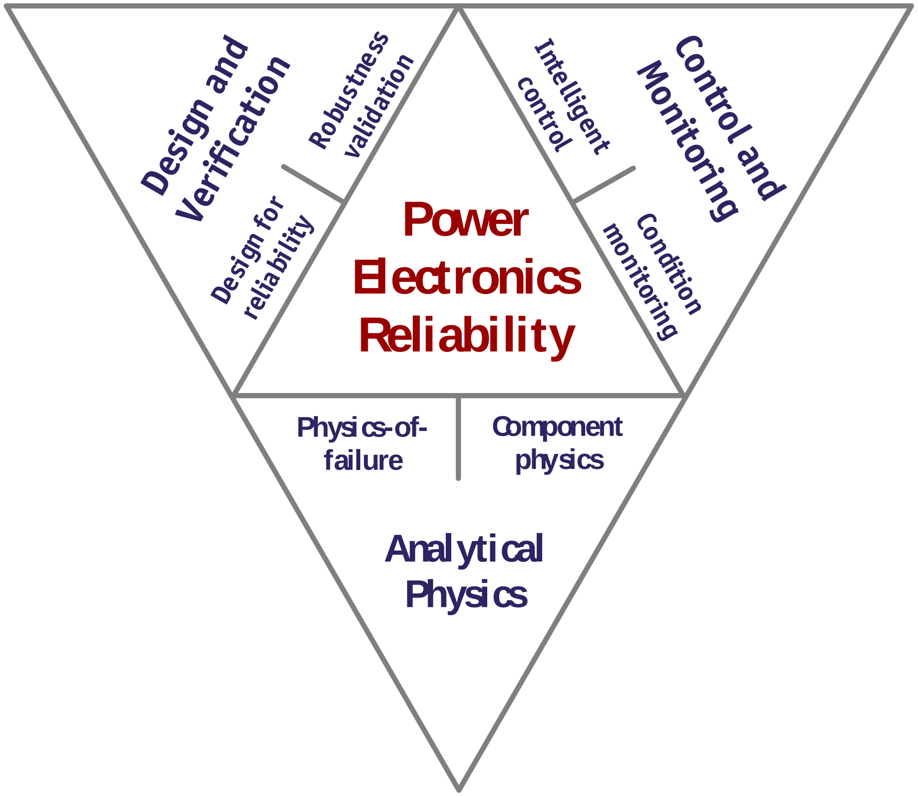
Stress analysis; Strength analysis

Stress control; Strength derating

Design at end-of-life; Consider the variations

The Scope of Reliability of Power Electronics

A multi-disciplinary research area

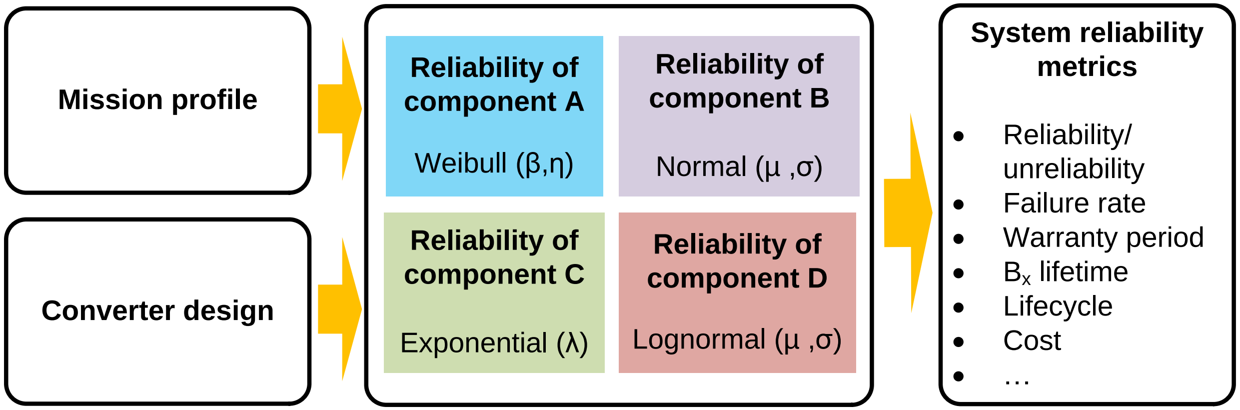


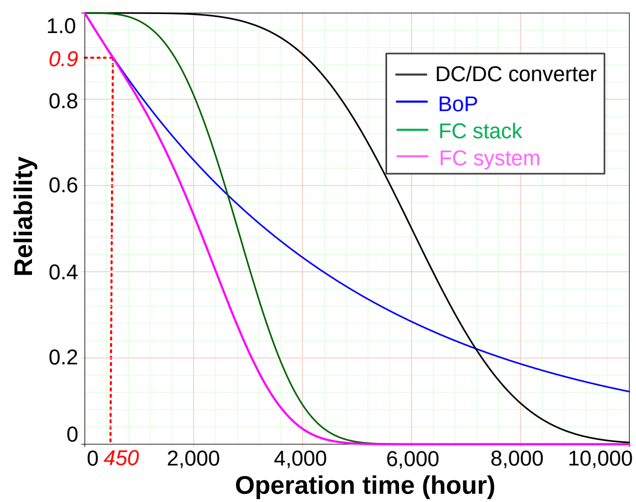
Paradigm Shift

- From components to failure mechanisms
- From constant failure rate to failure level with time
- From reliability prediction to also robustness validation
- From microelectronics to also power electronics

From Constant Failure Rate to Failure Level with Time

Component-level to System-level Reliability





Data source: S. Lee, D. Zhou, and H. Wang, "Reliability assessment of fuel cell system - A framework for quantitative approach," *in Proc. of ECCE 2016*, pp. 1-5, 2016.

Reliability-Oriented Product Development Process


(Source: PV Powered Inc.)

Concept

- Mission profile
- Topology and system architecture
- Risk assessment (e.g. new technology, new components)
- Existing database

Design

Validation

- System level functionality testing
- CALT
- HALT
- MEOST
- Robustness validation

Production

- Process control
- Process FMEA
- Screening testing (e.g. HASS)

Release

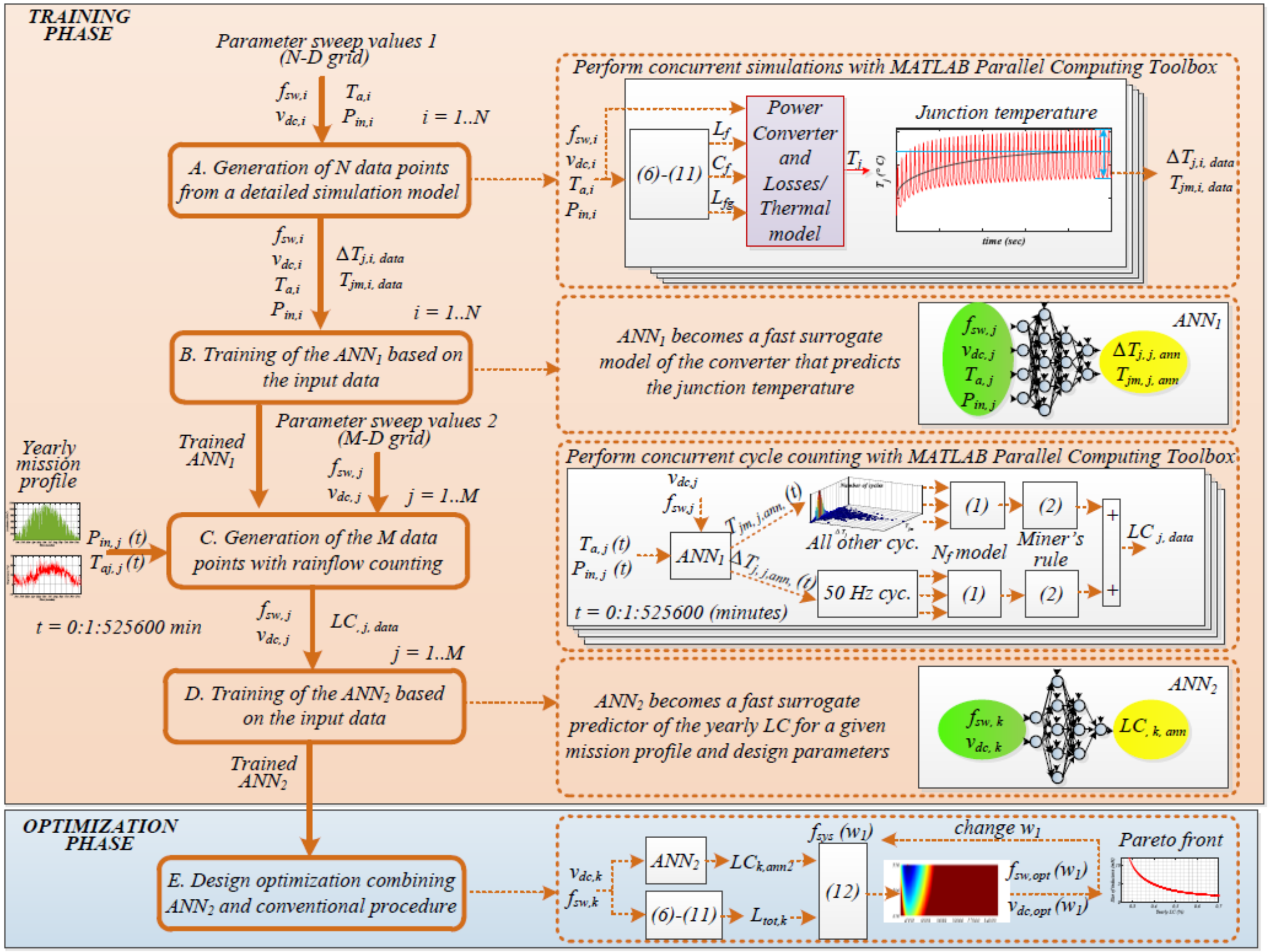
- Customer usage
- Condition monitoring
- Field data
- Root cause analysis data
- Corrective action data

(HALT – Highly Accelerated Limit Testing, CALT – Calibrated Accelerated lifetime testing, MEOST – Multi Environment Overstress Testing, FMEA – Failure Mode and Effect Analysis, HASS – Highly Accelerated Stress Screening)

How to design for power electronic systems?

Design for Reliability with Artificial Intelligence - workflow

- A surrogate reliability model of converter is created
  - It provides same results as detailed model, but 8 orders of magnitude faster



Reliable Power Electronics – Quo Vadis

- A mind-set change is important in power electronics circuit design – also in curricula of engineers
- Physics of failure models need to be developed further
- Go beyond temperature – challenge Miners rule
- Models can also be used effective in condition monitoring
- Reliability is also useful in service and new business
- Highly need for better life time models
- Highly need for smart testing methods to reduce testing time and thereby cost
- IoT and other will make oceans of possibilities
- Better integrated design tools to assess systems
- Design automation eg. with AI

IEEE Design Automation for Power Electronics

IEEE

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IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

CEDA®
IEEE Council on Electronic Design Automation

IEEE Design Automation for Power Electronics

DAPE Workshop

IEEE PELS and IEEE CEDA will hold the second Design Automation for Power Electronics (DAPE) workshop on Friday, September 6, 2019, the day after and in the same venue as EPE 2019 ECCE Europe at the Magazzini Del Cotone Conference Centre, Genova, Italy.

The purpose of this workshop is to understand the problems of Design Automation in Power Electronics, identify methodologies that have been used so far by academia and industry and identify the tools that have been developed to resolve the issues during design. The focus of the workshop is to bring together the experts in both power electronics and design automation and have them presenting their perspectives on the emerging needs.

The workshop is organized as a single-track event with two technical lecture sessions and one world café discussion session. The organization of the lecture sessions will contain talks from academia and industry. Afternoon sessions will be divided into groups to work on questions that are of interest for the community. For each group one set of questions is answered for 20 minutes and documented by the table-host. After the first round, the groups are mixed and the participants work in another group on another set of questions for ten minutes before the moderator/table-host reveals the results documented from the first round. In this manner, the workshop participants will actively provide their input as to where the design automation field needs to go to best serve the needs in power electronics design activity.

The workshop is especially good for:
Designers in the field of power electronics, packaging, and systems;
Providers of design automation tools including simulation, physical design, and design for reliability;
Manufacturers of test and characterization equipment for high-power, high-voltage systems;
Researchers in universities and research labs working on power electronic design automation.

September 6, 2019

Registration Fee: €100

Magazzini Del Cotone Conference Center, Genova, Italy

Co-Located with IEEE EPE 2019 ECCE Conference

Invited Speakers From Industry and Tools, Academia and the Scientific Agencies

Workshop General Chair: Alan Mantooth, University of Arkansas

Workshop Organizing Committee:
Miroslav Vasic, Polytechnic University of Madrid
Yarui Peng, University of Arkansas
Peter Wilson, University of Bath
Kevin Hermanns, PE-Systems GmbH

More information online at https://e3da.csce.uark.edu/dape/

Outlook

Power Electronics Technology – Summary

- Electricity creates the modern (and efficient) world
- Power Electronics – key technology for modern society – super scaling
- Cost of Energy go more down incl low failure-rate in renewables –
- Paradigm shift in power system operation with renewables and storage

- WBG will radical change power circuit design – few new power converters will be invented…
- Components need to be further developed – and modelled
- Passive components are a challenge

- Reliability engineering continue its development – complex
- Better reliability – more income on service for manufacturers

- Stability issues in solid state based power grid as well as conventional power system
- More stringent grid codes will still be developed – new demands

- Electrification of transportation – the large application for next two decades
- AI can assist in design, control and condition monitoring

- Rewrite our curriculums

- And much more..

Acknowledgment

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from Department of Energy Technology
Aalborg University

Look at

www.et.aau.dk
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Thank you for your attention!

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Department of Energy Technology
Aalborg, Denmark

AALBORG UNIVERSITY
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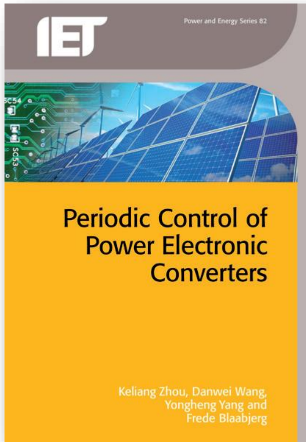

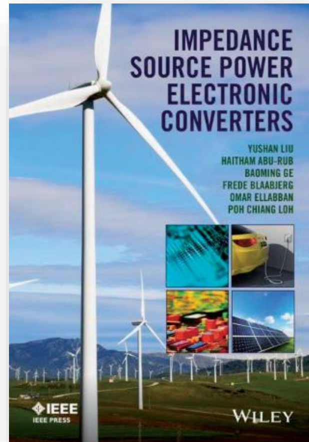

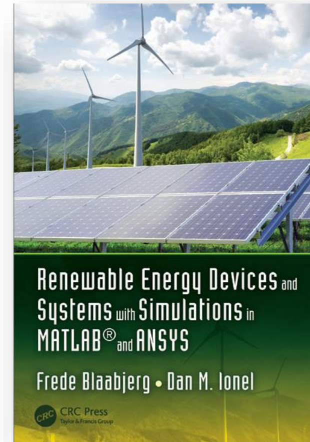

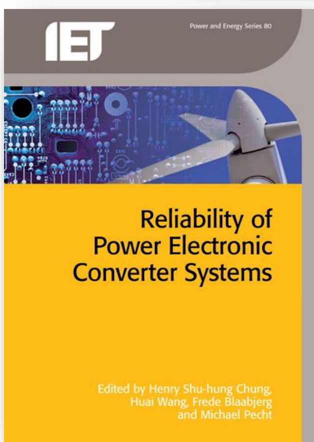

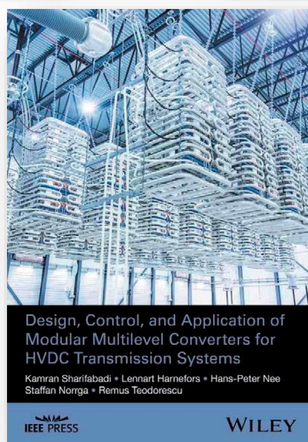

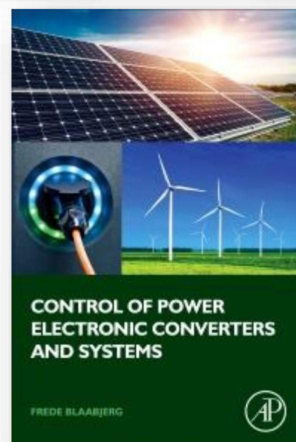

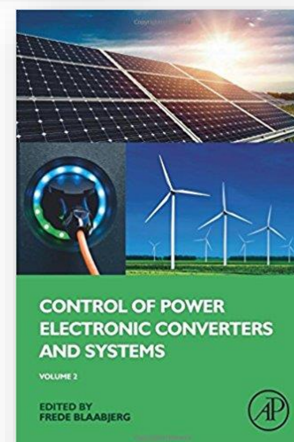

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