Presentation to University of Manchester R&D of Power Converters for Multi-MW Wind Turbine Generators

Philip Waite. Chief Engineer Power Converter CoC, Keele UK 27 April 2018

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Eur.Ing **Philip Waite** **BSc, CEng, MIET ,**
Chief Engineer, Power Converter CoC, Keele UK

Personal Resume

•1984: Graduated Sheffield Polytechnic: Control Engineering

•1980-2007: Sponsored Student/Employed by GEC/Cegelec/Alstom/Converteam (now GE)

- Junior Engineer to Development Manager involved with with hardware/software development and application of advancing technology ranges of variable speed ac drive products (frequency converters) 4-4000kW, 380-690V.
- Typical Applications:
  - Steel process lines;
  - Pumps, fans.
  - Electric Ship propulsion and steering.
  - Wind Turbine Generators (Bonus→Siemens Wind Power now Siemens Gamesa)

•August 2007: Joined Siemens Wind Power with 5 others to start-up Keele Power Converter CoC

- From "blank sheet", development of Full-scale Power Converter for 3-8MW direct drive Wind Turbine generators and development/validation facilities from concept through to volume manufacture/test.
- co-inventer of various patents incorporated in the design
- ~8GW now operational currently operational

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Contents

- Brief company profile
- Explanation of Driving forces for R&D : Levelised Cost of Energy
- Industry R&D challenges
- Key areas of technology development within a WTG (including Power Electronic Converter)
- UK locations of Centres of Competence (CoC) for Generator and Power Converter design and responsibilities

- Short Video from 2011 showing Prototype 6MW prototype Direct Drive WTG

- Closer look into the Power Electronic Converter used in our WTG
  - The functions performed by the converter
  - The basic topology of our frequency converter, and our specific implementation and why.
  - More detailed look at a specific area of design: Designing to meet the required product lifetime using knowledge of wear-out mechanisms and mission profile: IGBT module bond-wire fatigue

- Foreseeable future challenges

- Questions

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Company profile

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Siemens Gamesa Renewable Energy

Siemens Gamesa is a **leading provider** of wind power products and solutions to customers around the globe. The company has installed products and technology in more than **90 countries**, with a total installed base of close to **80 GW** and close to **27,000 employees**. Siemens Gamesa offers one of the industry's **broadest product portfolios**, with both **offshore** and **onshore** technology as well as industry-leading **service** solutions, helping to make clean energy more affordable and reliable. The united company was created in 2017. Previously, Siemens Wind Power's history in the wind industry extends back to the early 1980s, and Gamesa's to 1994. Additional information is available at the company's website: www.gamesacorp.com

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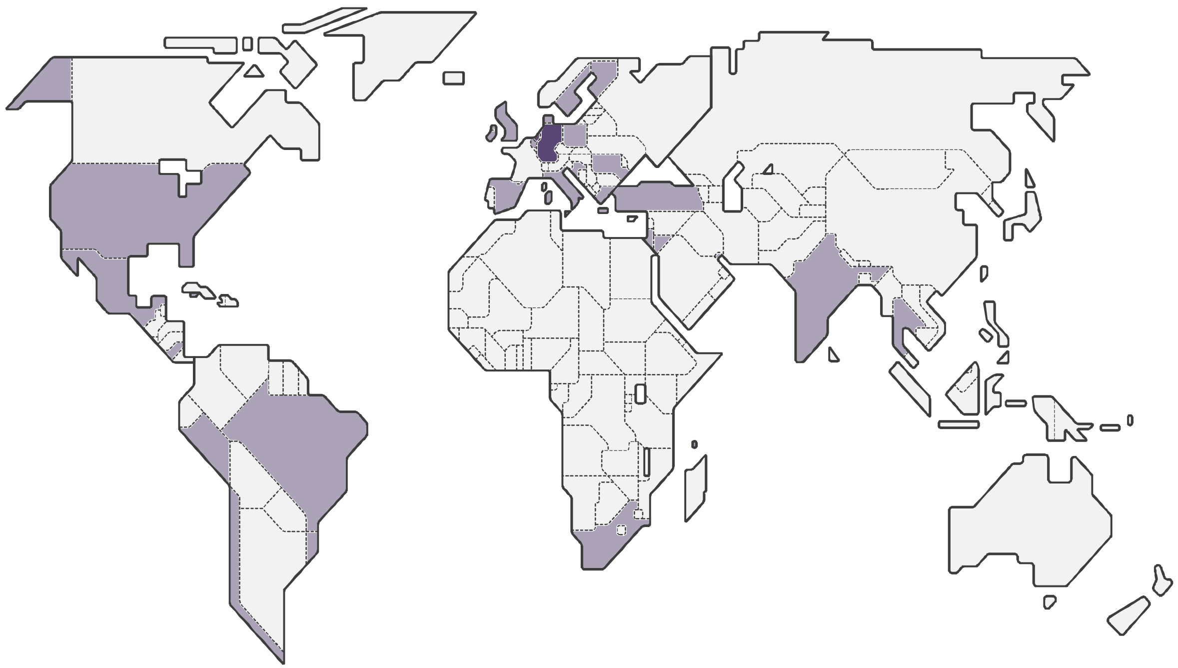
A leading provider of wind power solutions to customers around the globe

Offshore
- #1 in global Offshore market

Onshore
- #4 in global Onshore market
- #1 in India and LATAM

Service
- #2 in service backlog
- #2 in serviced fleet size

Top 3 market share* position in several main countries



Onshore Offshore

* Based on MW installations

Source: MAKE Global Wind Turbine OEM 2016 Market Share

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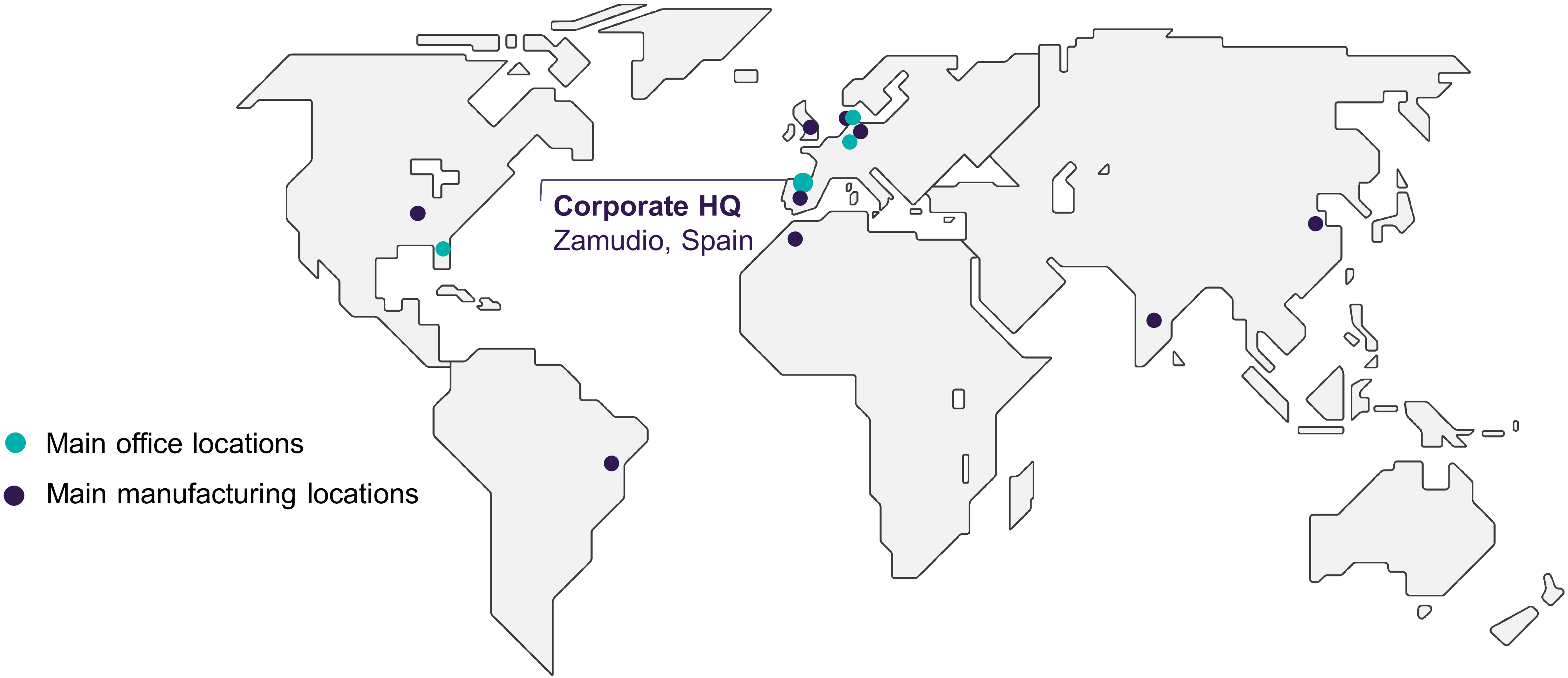
Company profile

Global presence



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Key facts

Order Book
€~20.4 bn

Annual revenue
€~11.5 bn

Installed capacity worldwide
~80 GW

Employees worldwide
~27,000

Market capitalization
€~8.2 bn[1]

Figures as of June 2017

[1]Calculated based on share price on October 17, 2017

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Three business units strongly positioned in the market

Onshore

+70 GW installed in 70 countries since 1980

The technological partner of choice for Onshore wind power projects.

Offshore

+9 GW installed worldwide since 1991

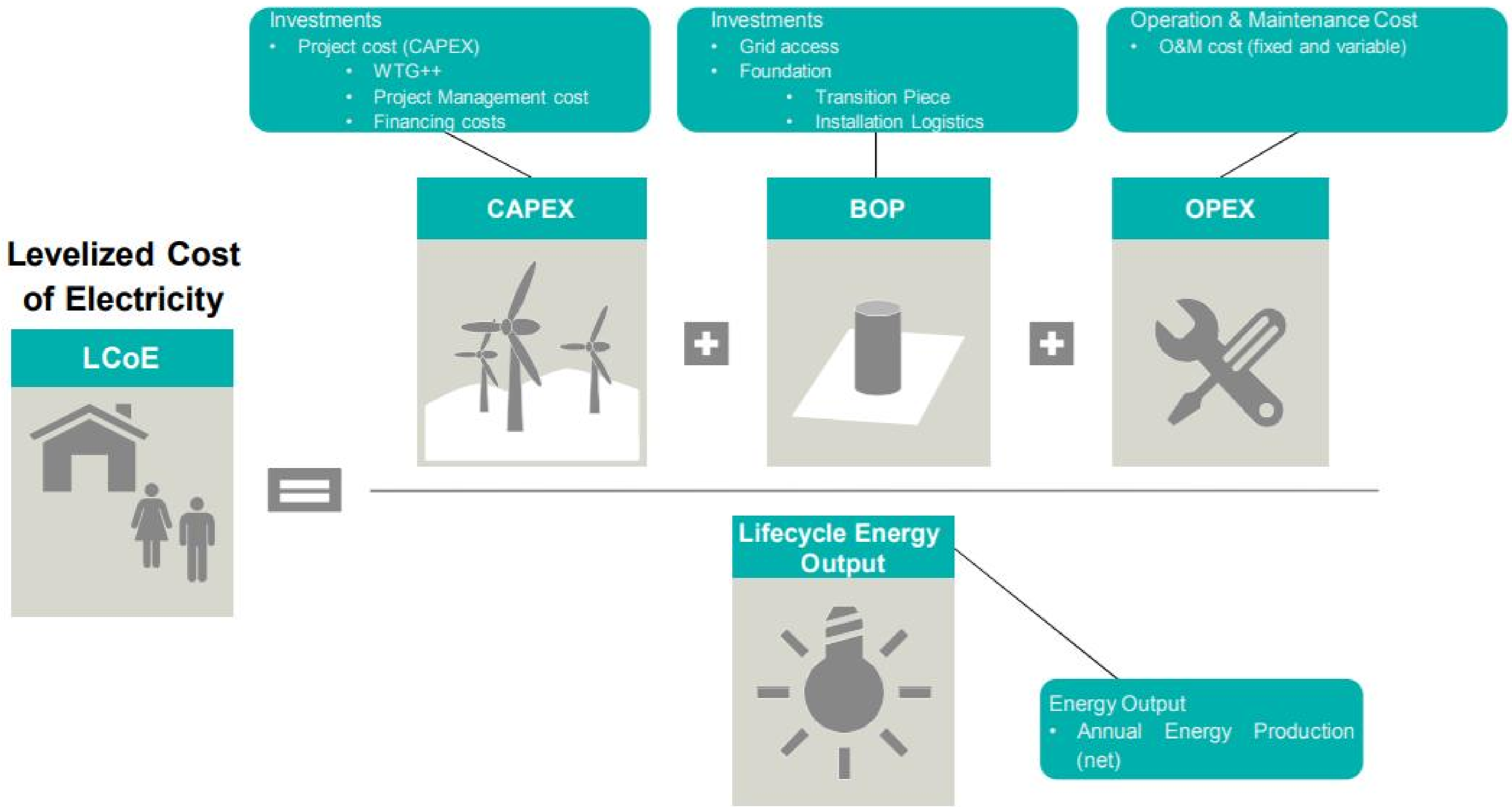
Most experienced offshore wind company with the most reliable product portfolio in the market.

Service

+53 GW maintained

Commitment beyond the supply of the wind turbine to reach the profitability objectives of each project.

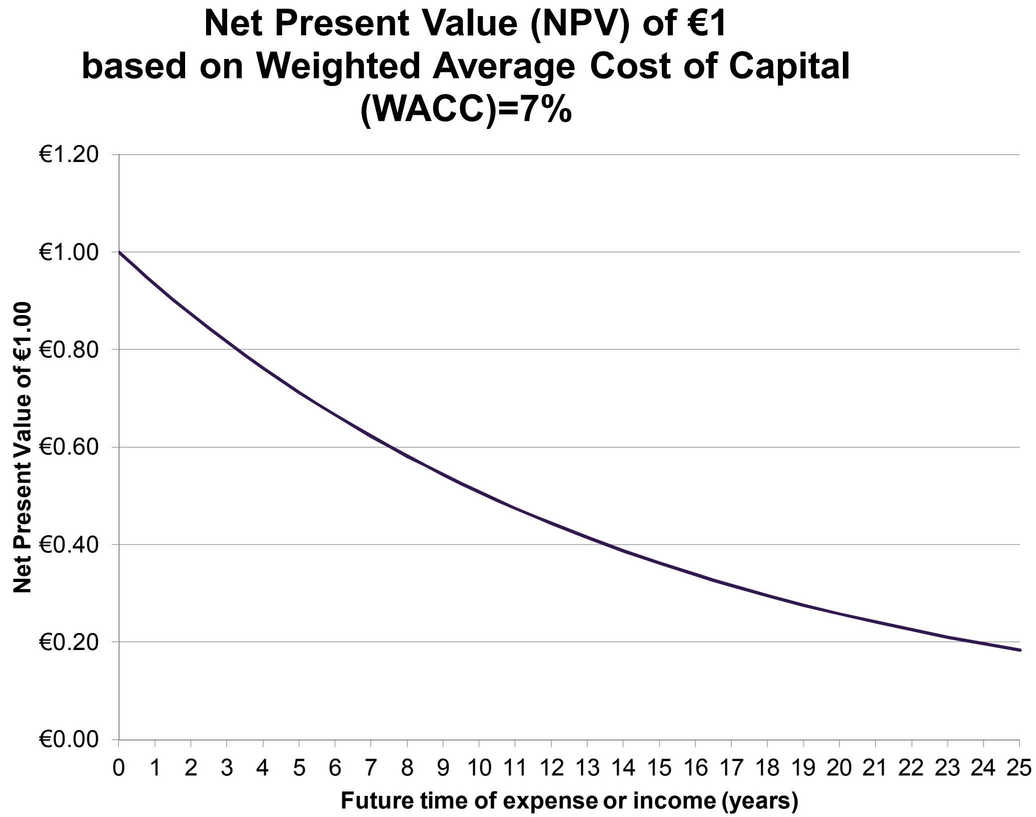
Holistic view on the costs and performance is the key for success



Levelised Cost of Energy (LCoE) and Net Present Value (NPV)

$$LCoE = \frac{\sum \quad NPV\ CAPEX + \sum \quad NPV\ OPEX}{\sum \quad NPV\ Energy}$$

- CAPEX= Total up-front cost of installing the equipment
- OPEX= operational expenditure over the lifetime of the generator : fuel maintenance
- Energy = Energy produced over the lifetime



The only reason wind farms exist, is because they represent a competitive financial investment for investors !

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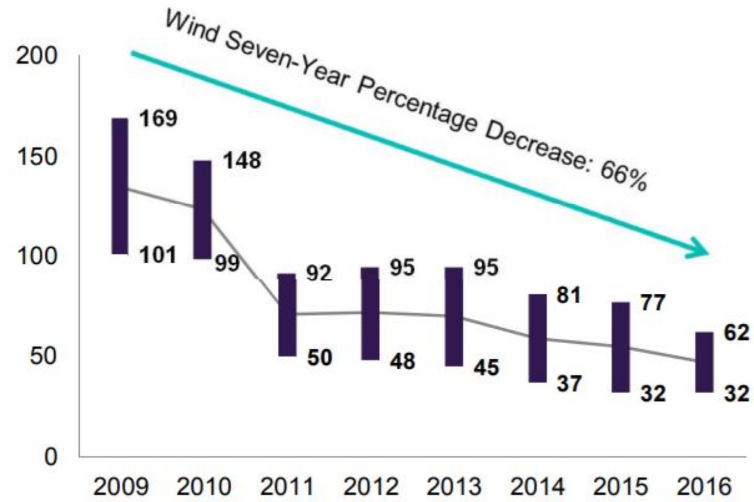
Wind power needs to be competitive with all energy sources

Levelized Cost of Electricity – Wind



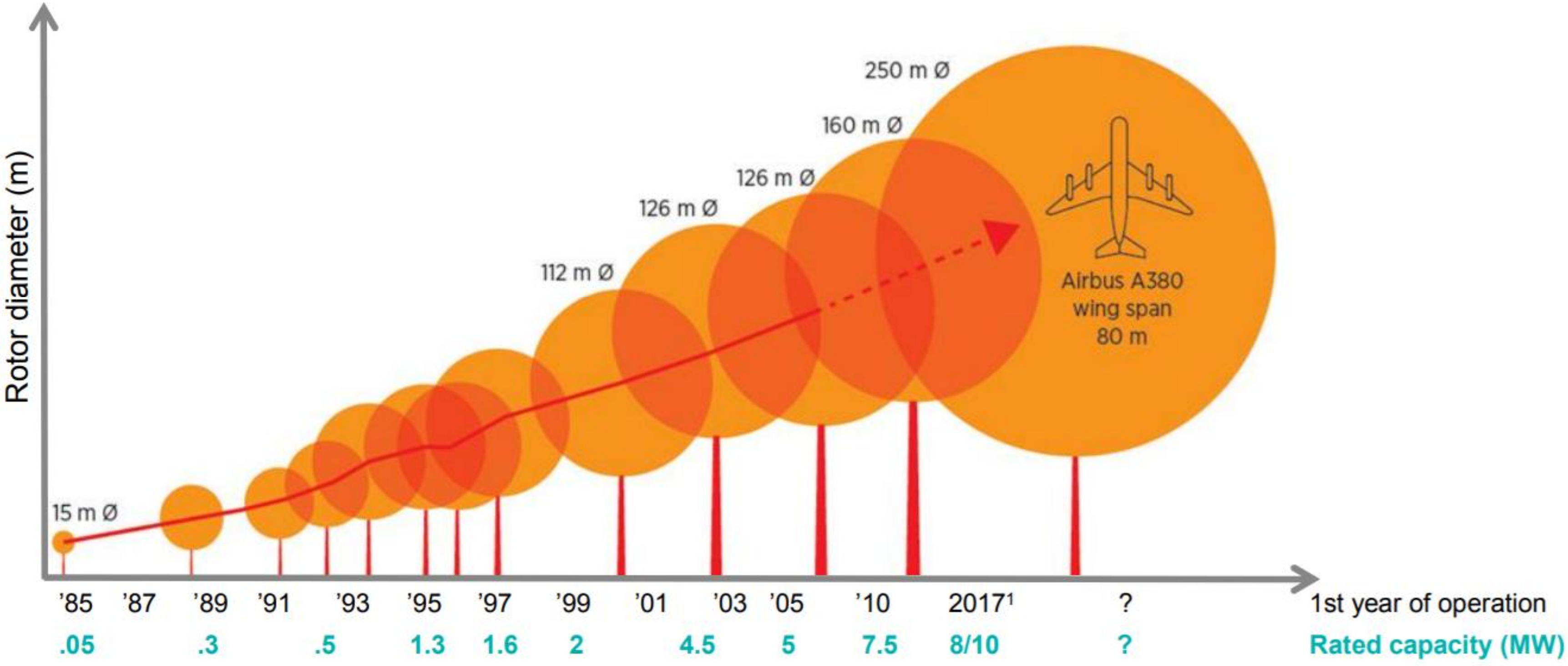
Source: Lazard – Levelized Cost of Electricity ver 10.0, December 2016

Unsubsidized Levelized Cost of Energy Comparison

Continuous focus on cost required to compete with alternative energy sources

Wind technology design needs to enable machines never built in that size before

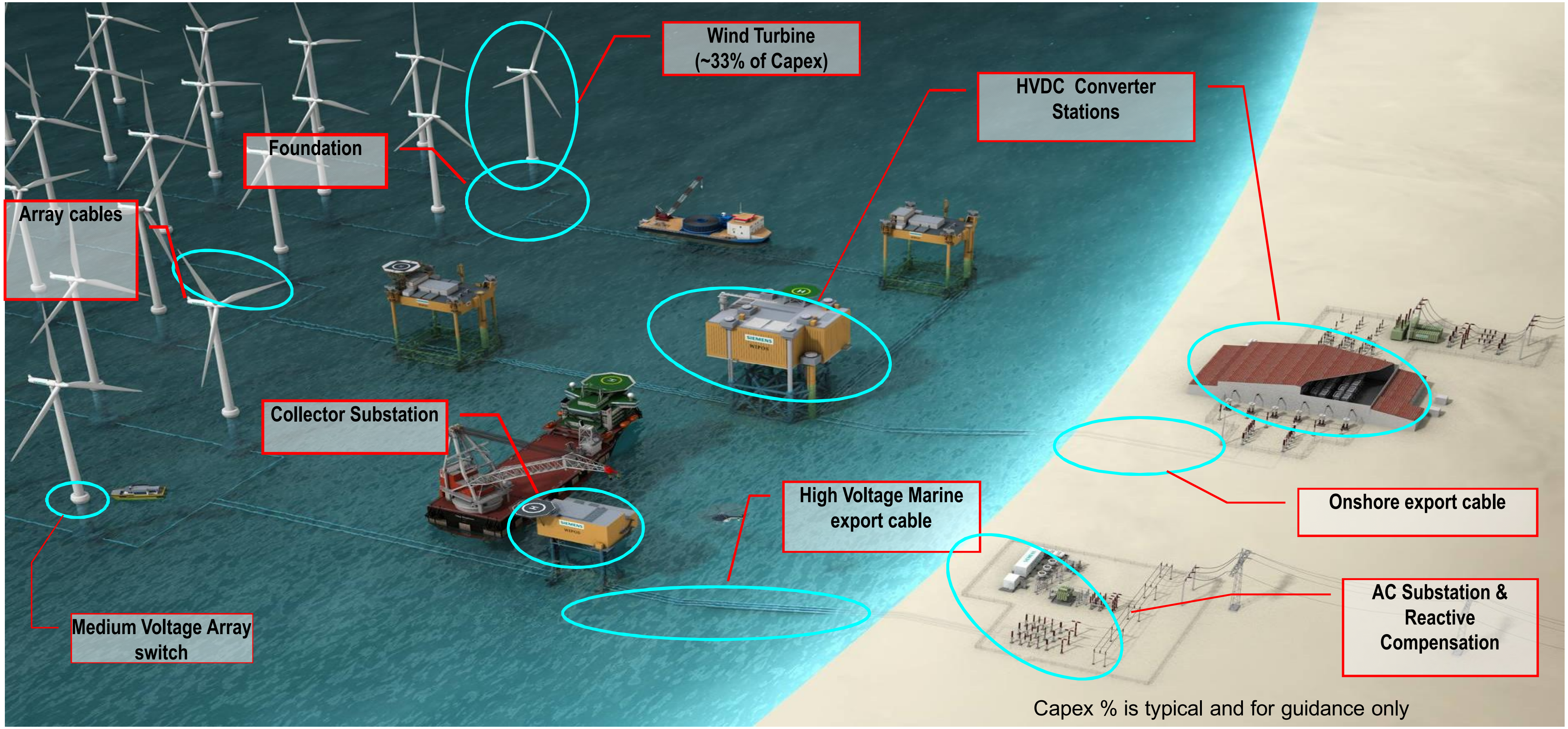
Growth in capacity and rotor diameter of wind turbines, 1985-2016



Source: Wind Power Technology Brief, International Renewable Energy Agency (IRENA), March 2016

1) Expected

Elements Of Offshore Energy Generation & Grid Connection



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Wind market is characterized by high development cost and complexity

Automotive

- High R&D cost
- Short product life cycle
- High volume
- Fast development

Aircraft

- High R&D cost
- Long product life cycle
- Low volume
- Slow development

Wind turbine

- **High R&D cost**
- **Short product life cycle**
- **Low volume**
- **Fast development**

Innovation is required to handle the wind market development conditions

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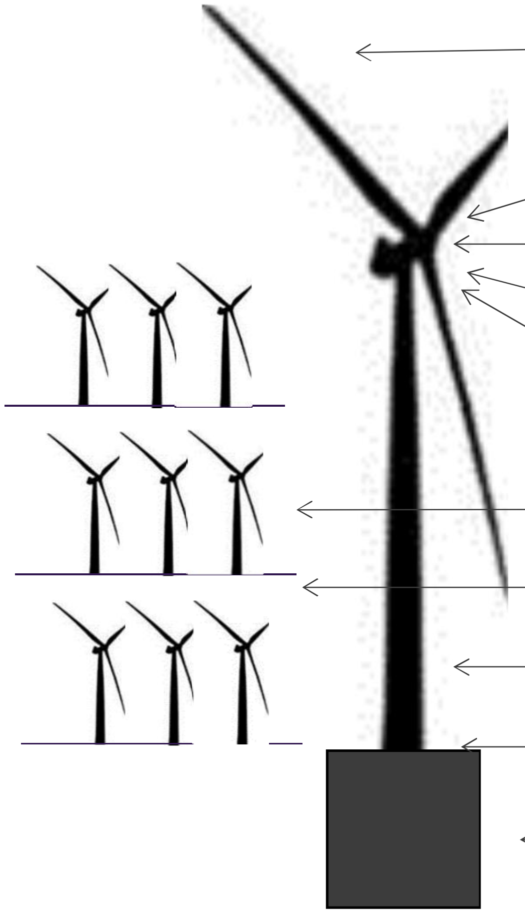
Technology Development (TD) Focus Areas



AREA	
Blades	
Generator	
Bearings	
Turbine Control	
Converter and Transformer	
WF grid connection	
Plant Control	
Tower	
Grid connection	
Structure	

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UK R & D Centres

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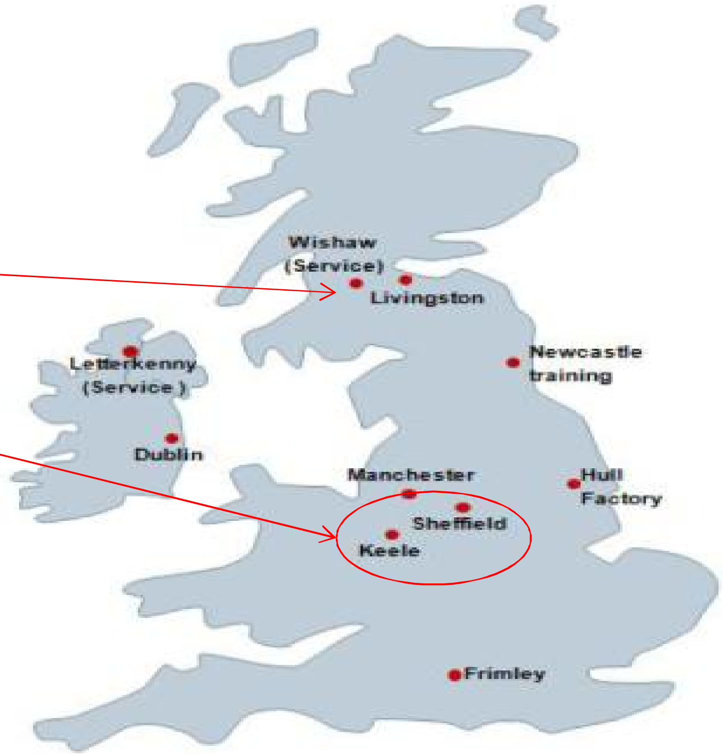
WP UK- Locations

- **Frimley (UK HQ)** – Main headquarters for UK operations
- ~~**Livingston** – Scotland Office~~
- **Dublin** – Ireland Office
- **Keele** – R&D office for Power Converters (+ Glasgow)
- **Sheffield** – R&D office for Generators
- **Manchester** – Regional office housing Construction department
- **Newcastle (Service)** – Training centre run by service but utilised by projects
- **Hull** – Site of Blades factory and offshore facility
- **Letterkenny and Wishaw** - Service



Keele, UK Power Converter Competence Centre

- **Mission –** To be the best at power electronics, control, application and design for quality manufacture for multi-megawatt power converters, specifically within the wind business and potentially other renewable energy sources

- **Scope –** To supply SGRE Turbines with the manufacturable designs, for power electronics, robust software and validated models, to ensure the right technical solutions required by the business to remain best in the wind industry.

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Power Converter Competence Centre Core Tasks & Responsibilities

•Design, Prototype & Validate Power Converter Modules, software, control and models

•Deliver and support validated products to the internal customer: the various WTG platforms

•Generation of IP in all areas, inclusive of Patents

•Develop and implement electrical wind turbine and wind farm client user models for grid code and TSO required assessment studies

•Research into, and evaluation of, alternative technologies according to the Product and Technology Roadmap

•Support of Wind turbine system software developers.

•Responsible for production lines manufacturing Power Converter products.

•Support OEN to provide high performance, full validated, grid code compliant models to the regions & clients.

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The Power Converter

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Video 6MW Prototype

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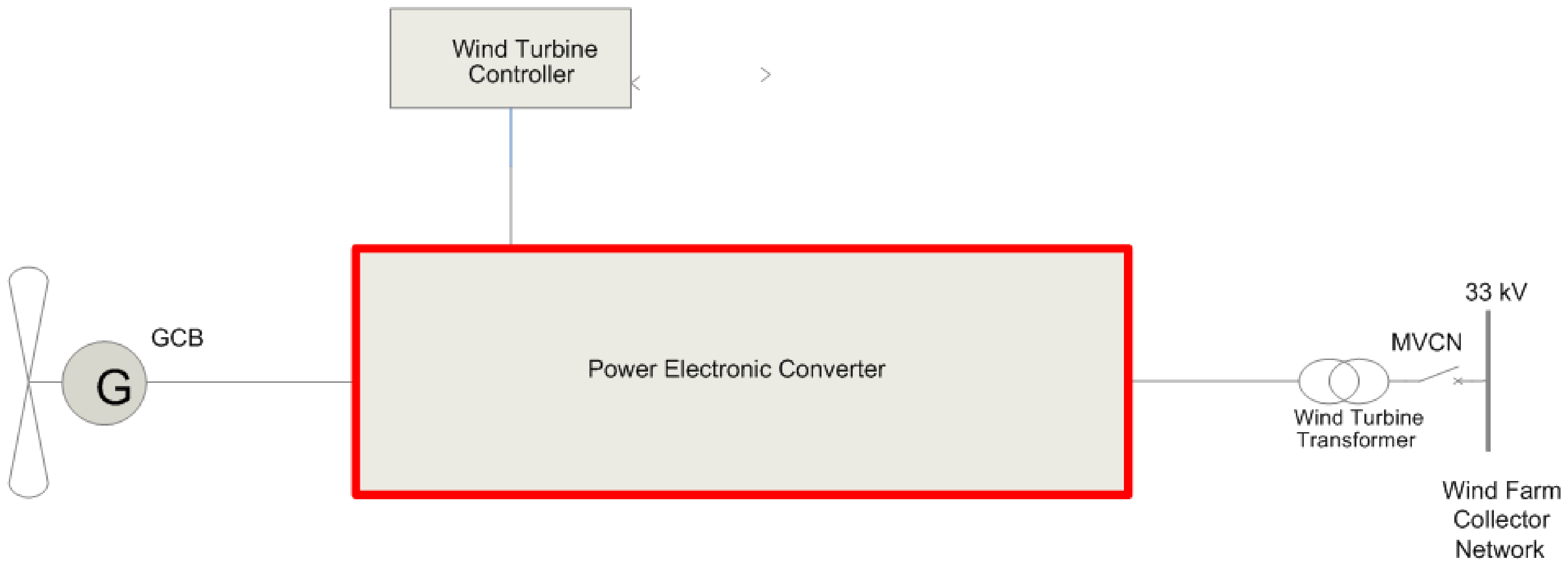
Overview of Wind Turbine Converter



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Primary Functions of the Converter

Generator side

- Regulation of power from the variable speed generator to the grid
- Smoothing of power flow caused by wind speed fluctuations, and generator torque ripple and other effects
- Damping of mechanical resonances in the drive train and tower
- Torque ripple cancellation from generator

Grid side

Meet the requirements set out in the specific grid codes that cover the requirements of international customers relating to “power quality” under specific steady state and transient conditions

Power quality

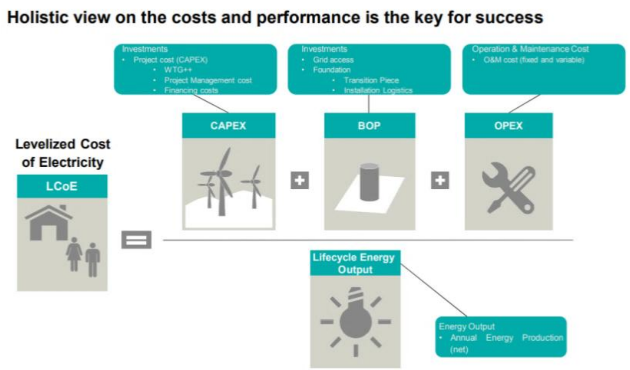
- Voltage amplitude
- Harmonic distortion
- Frequency/phase
- Transients

Grid events

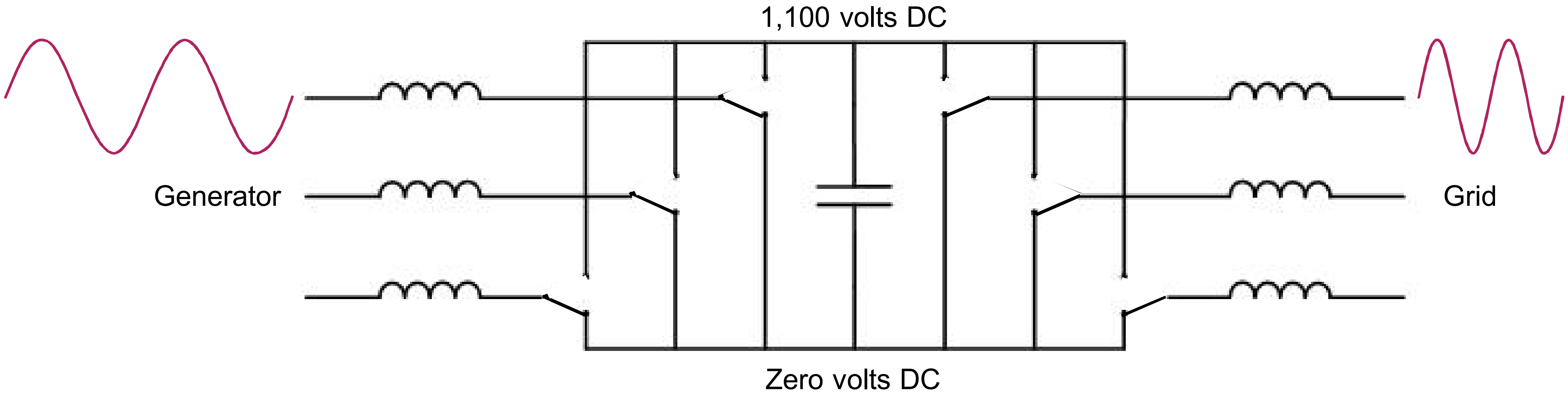
- Low voltage ride-through
- High voltage ride-through
- Rate of change of frequency and phase jump events
- Transients e.g. due to capacitor bank switching

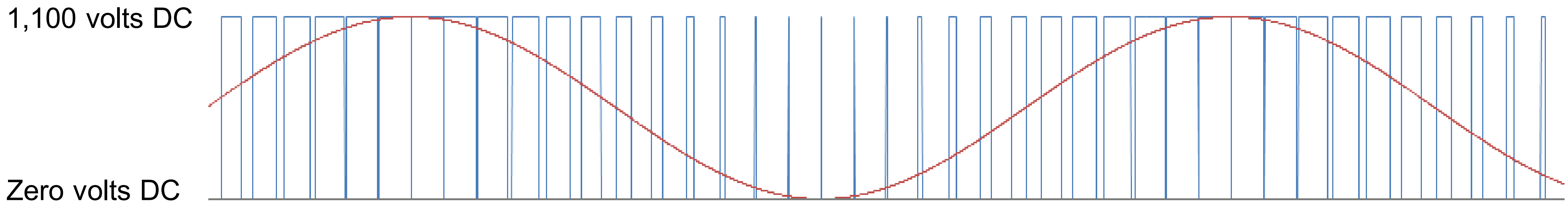
Converter System Design Factors for WP

- **Overall cost** of electrical system (Transformer, Incomer, Filter, Converter, Generator, Cables).
- **Operational costs** of electrical system (routine maintenance requirements).
- **Total system efficiency** and losses.
- **Development costs, effort and time** to realise a serial product. (Logistics).
- **Reliability**, availability, MTBF, MTTR. (Impact on AEP).
- **Size** – Height, width, depth. Weight.
- **Simplicity** – low parts count. (Impact on cost and reliability).
- **Commercial risks** + necessary business partnerships. The “whole business” view.
- **Compatability** with existing control strategies and SICS control system. (Logistics, IP retention…)
- Technical advantages/disadvantages against **competitors likely solutions**
- **Technical risks**. (Conservative approach, or should we be bold).
- Annual Energy Production (**AEP**) comparisons. (Does one solution give more energy produced over the lifetime of the turbine.

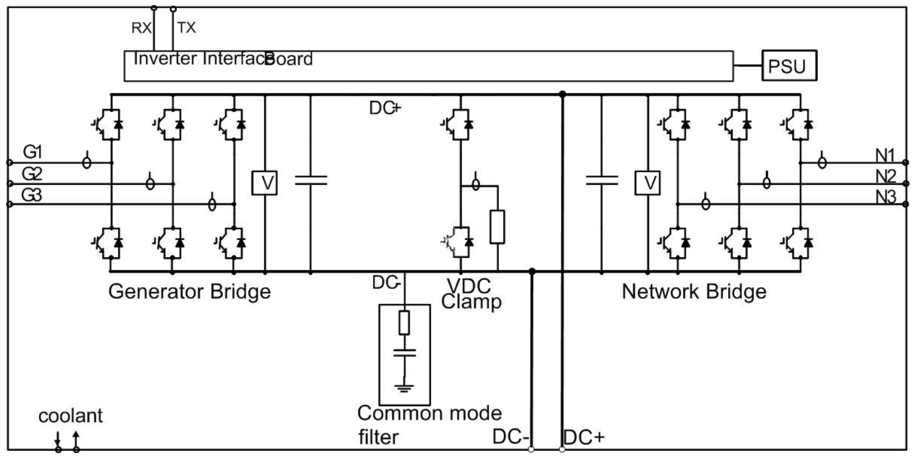


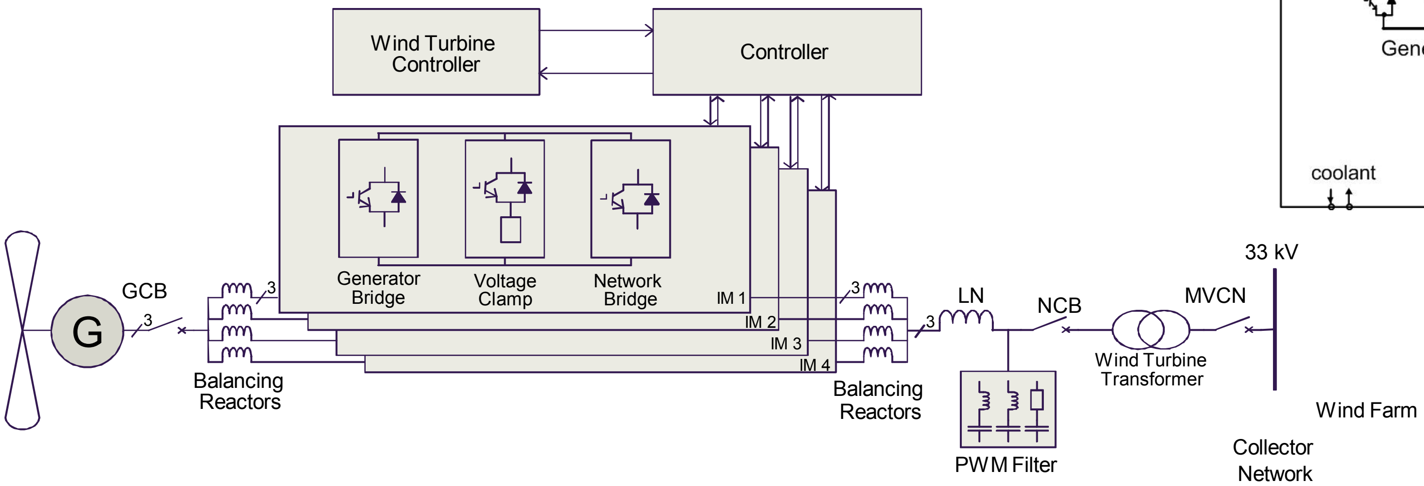
Simplified circuit diagram of converter

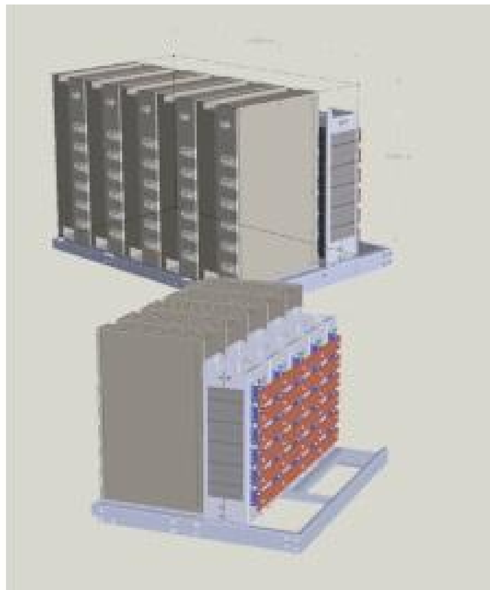




Wind Turbine Converter







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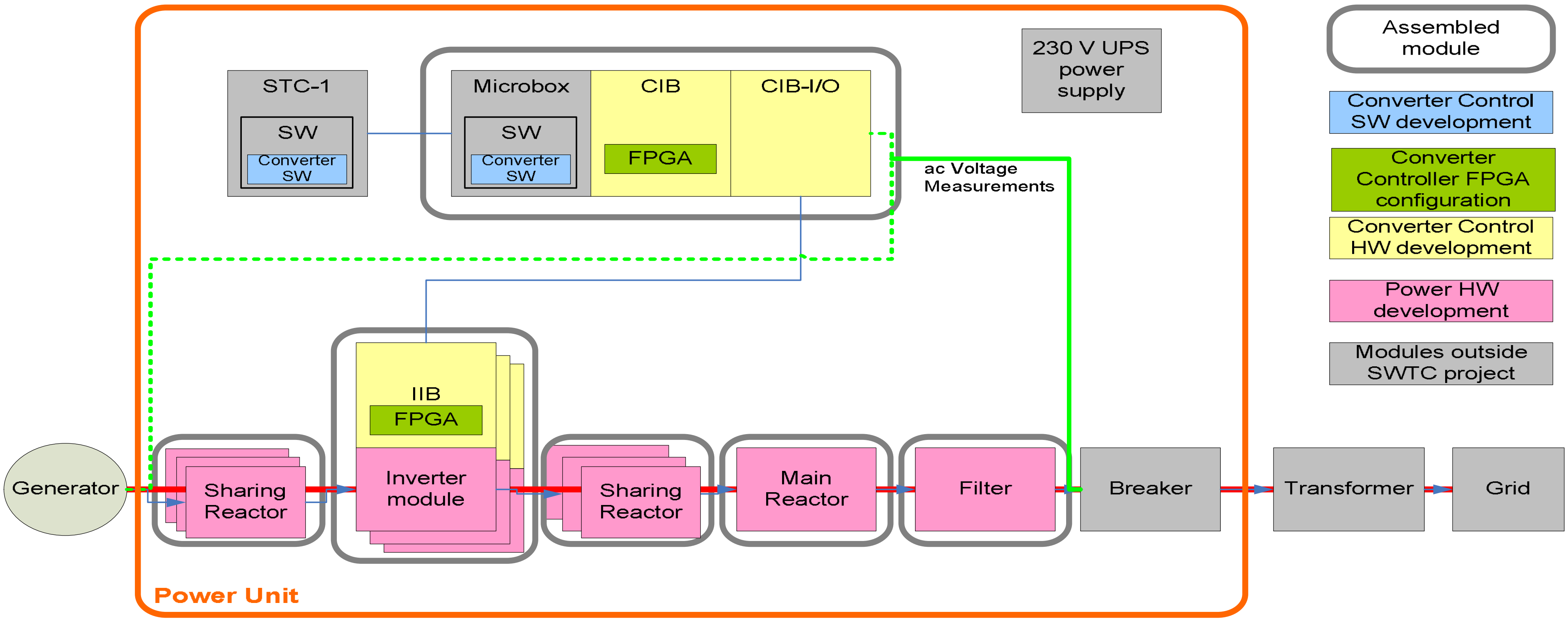

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Example of a detailed design solution: Designing IGBT utilisation to meet Turbine lifetime

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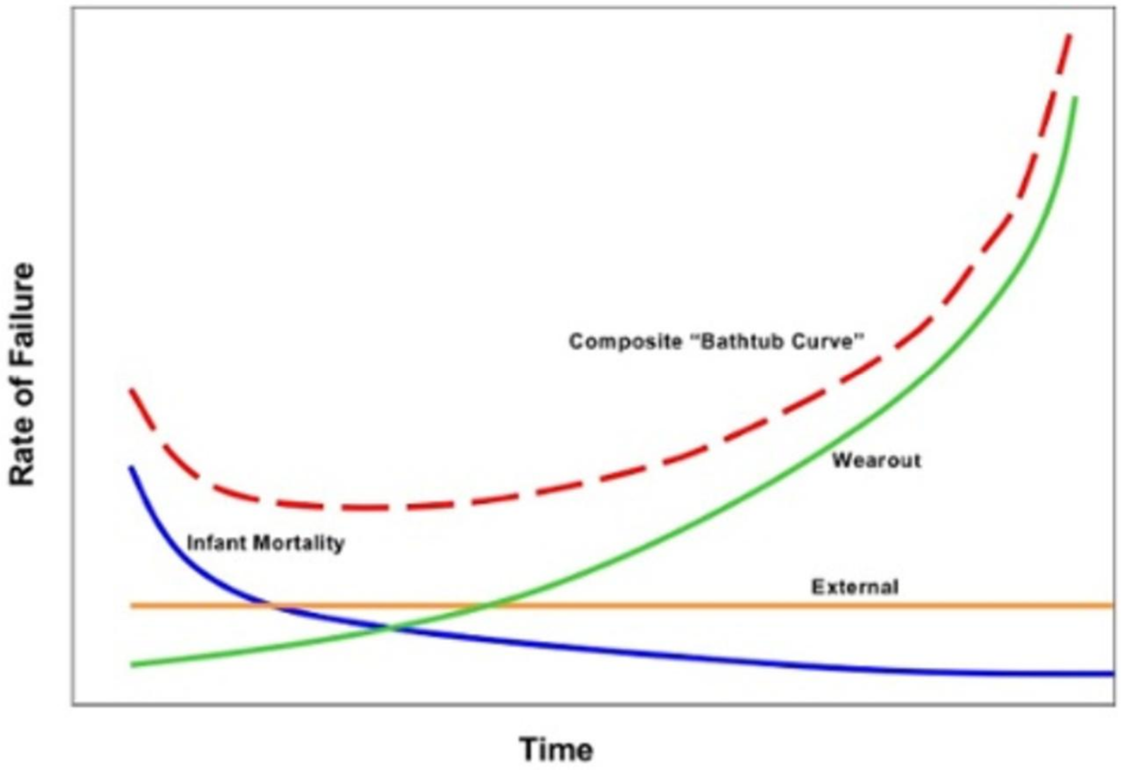
Types of failures



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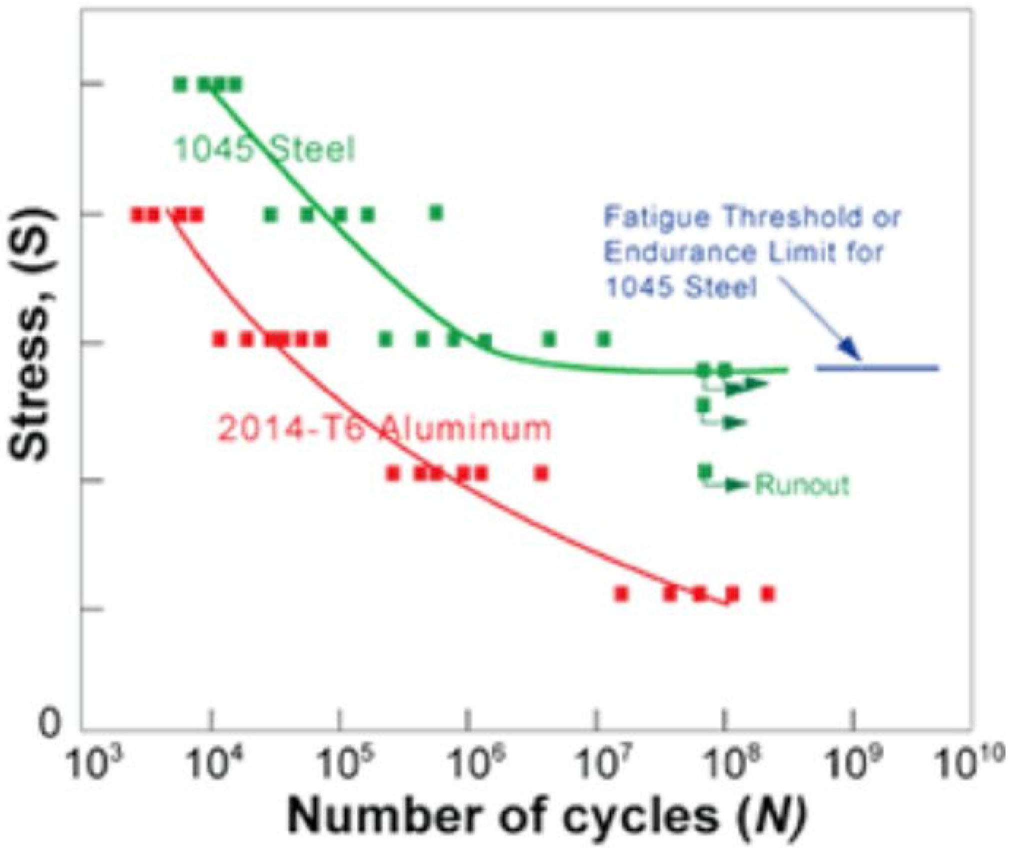
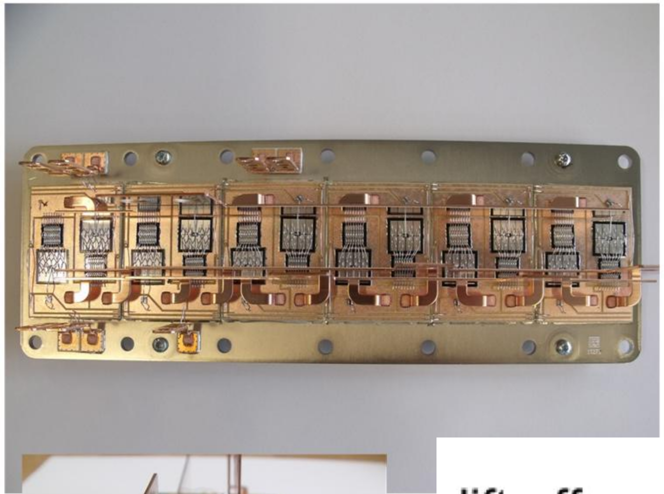
Examples of “wear-out” mechanisms

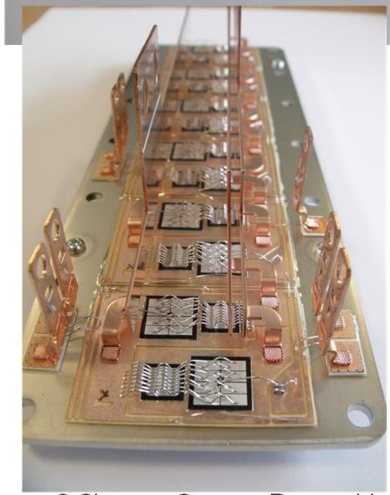
- Corrosion – steady loss of material over time leads to failure
- Wear – material loss and deformation, especially loss of protective coatings
- Radiation – Ultraviolet, X-ray, nuclear bombardment in environment changes molecular structure of materials
- Fatigue – repetitive cycle of stress wears out material

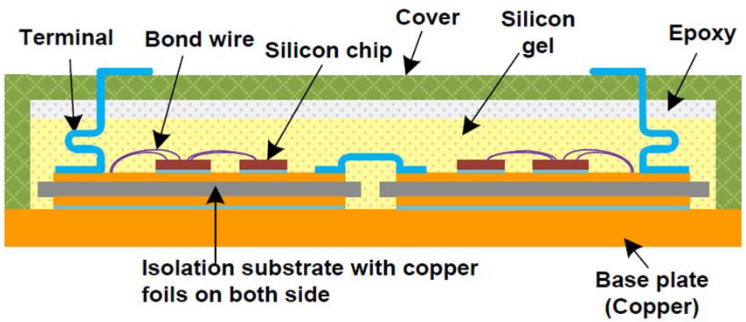
Characterisation of fatigue “ S N Curve”

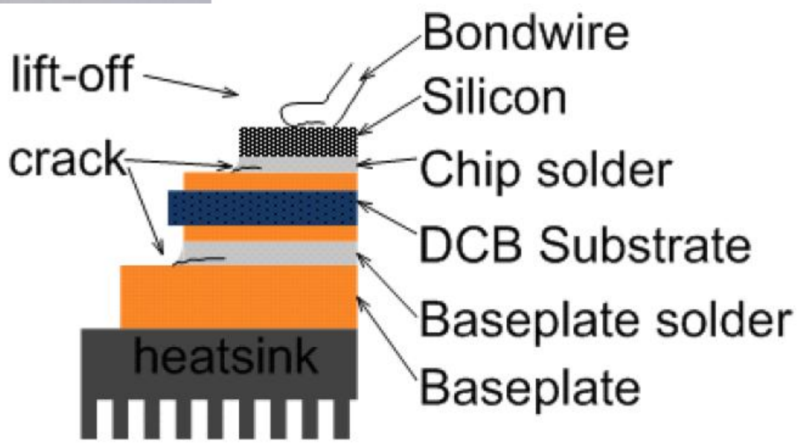


Different Fatigue wear out in IGBTs



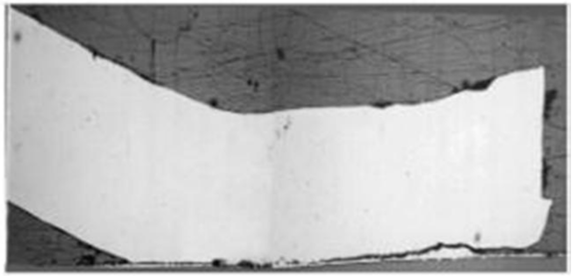




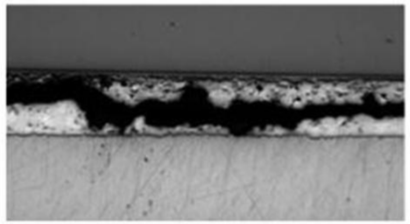


Three major regions for thermomechanical failures

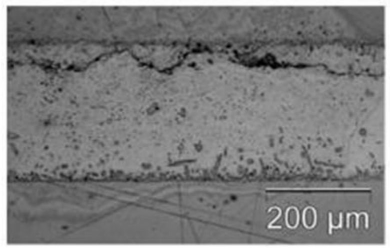
■ Bond wire lift-off



■ Chip-to-substrate joint



■ Substrate-to-baseplate

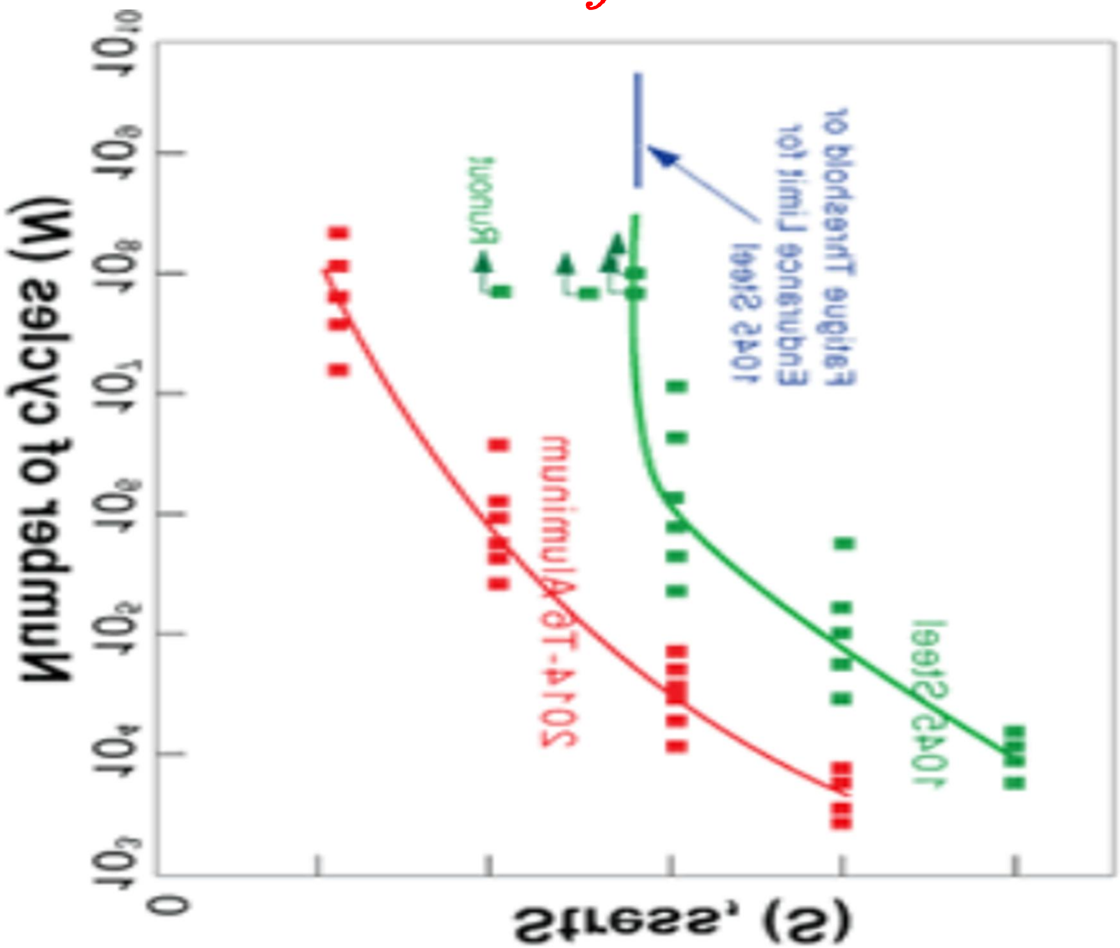


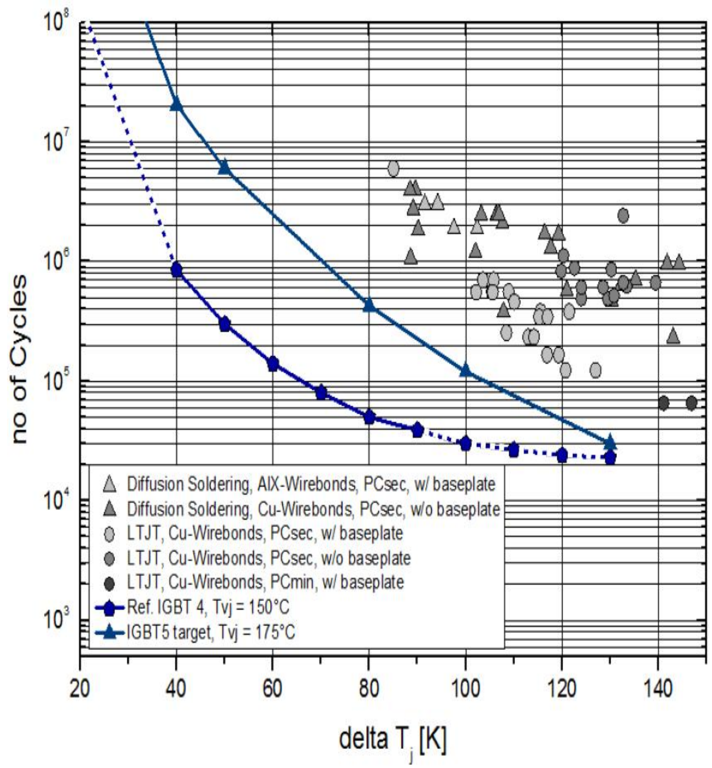
Large differences in coefficient of thermal expansion

Material	Coefficient of linear expansion (ppm/K)
Aluminium	23
Silicon	3
Aluminium Oxide	7
Copper	17

Characterisation of Fatigue

Thermal Cycle





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What causes the thermal cycling ?

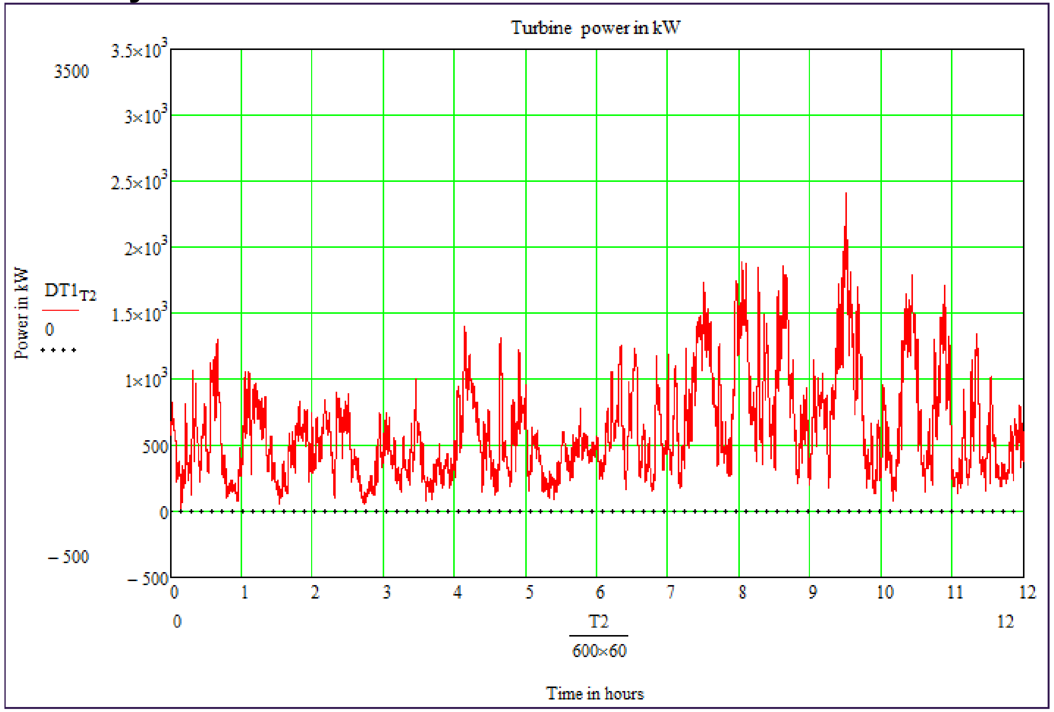
•1 Load variations

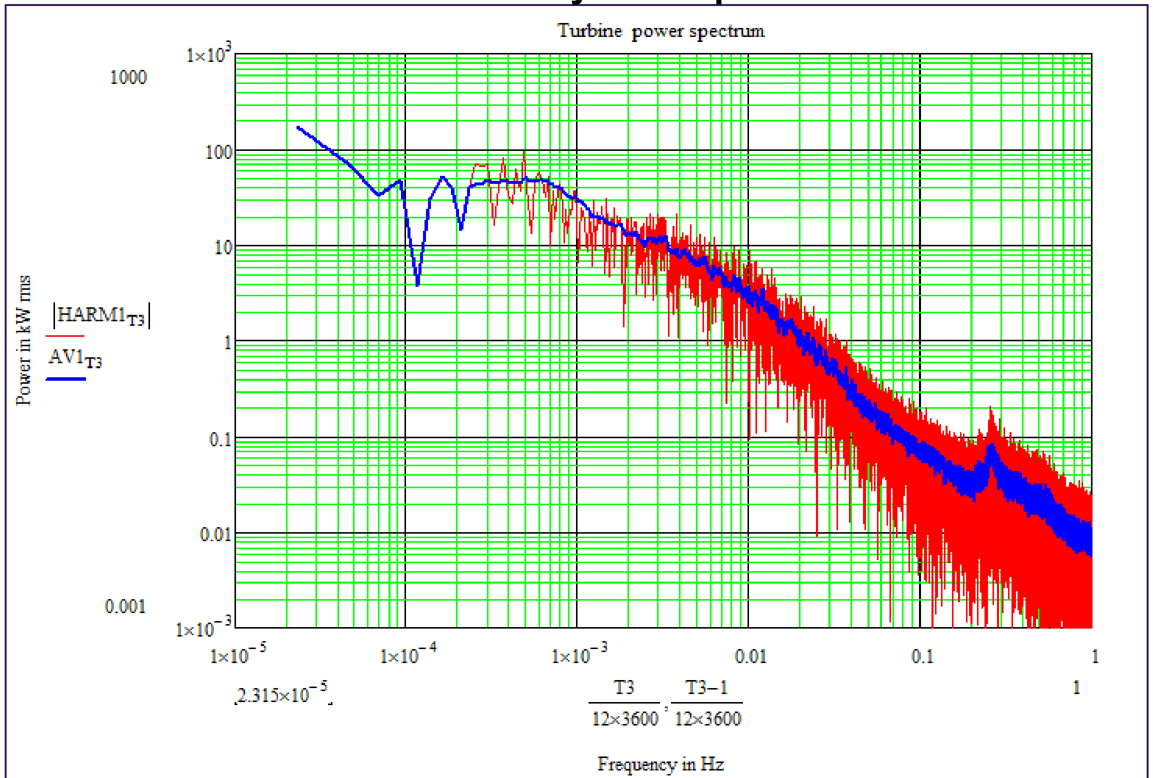
•Temperature within IGBT is a function of turbine power

  •Power cycling of wind turbine occurs due to wind speed variation

The cycle time of load variations are >>1s

ie load variation thermal cycle frequencies are <<1Hz





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What causes the thermal cycling ?

•2 Power Variations within the Semiconductors within the IGBT Module

(For which we first need to understand a bit how the Inverter works)

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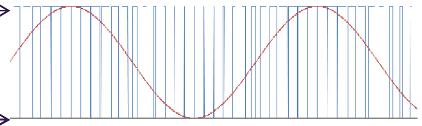
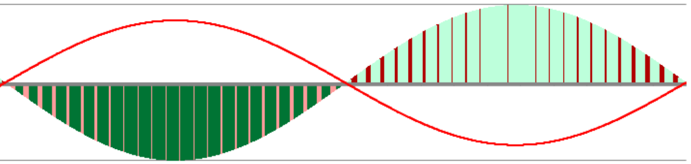
Loading of the individual semiconductors

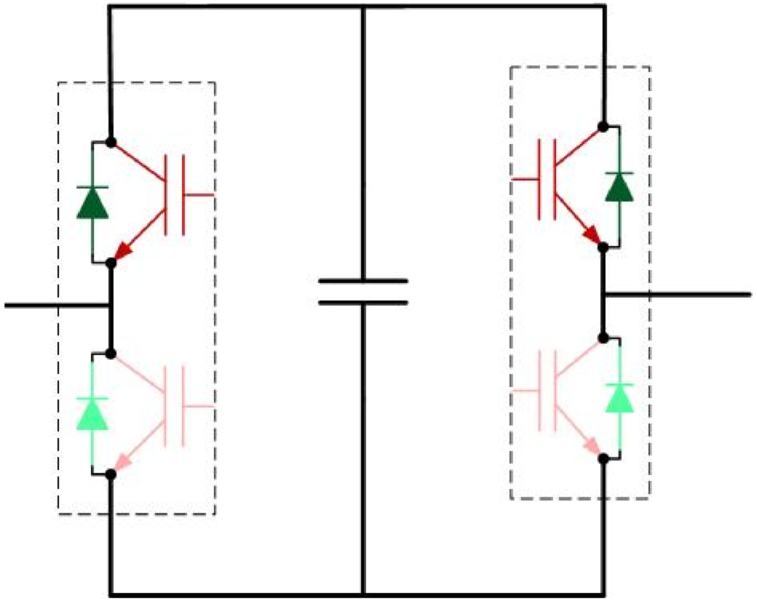
Top IGBT “switched on”/ Bottom IGBT “switched off”

Bottom IGBT “switched on”/ Top IGBT “switched off”

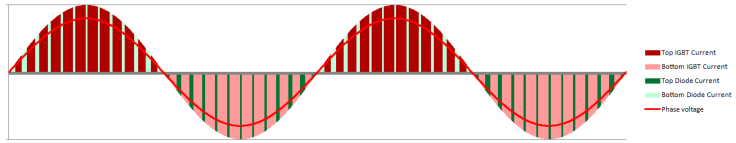


Generator Bridge ~ 12Hz
 “Negative” power flow
Ie Power flows **into** inverter
Ie current and voltage are opposite polarity





Network Bridge 50Hz or 60Hz
“Positive ” power flow
Ie Power flows **from** inverter
Ie current and voltage are same polarity



- **Current can only flow through the IGBT or Diode in the direction of the arrow**

- **The colour of the shaded current waveform corresponds with the colour of the IGBT and Diodes that the current is flowing in !**

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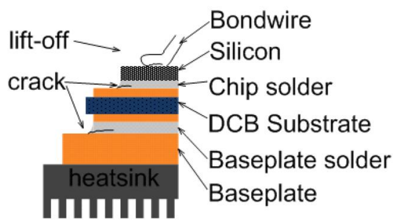
Which parts are affected by 12Hz and which parts are affected by <1Hz ?



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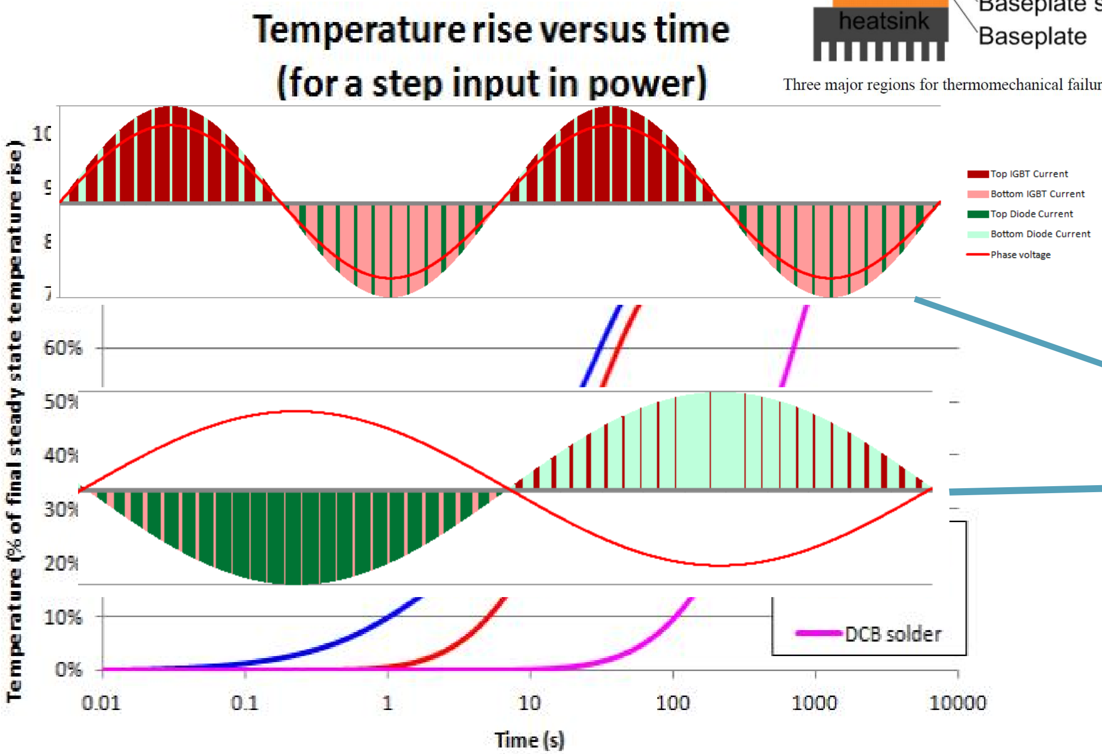

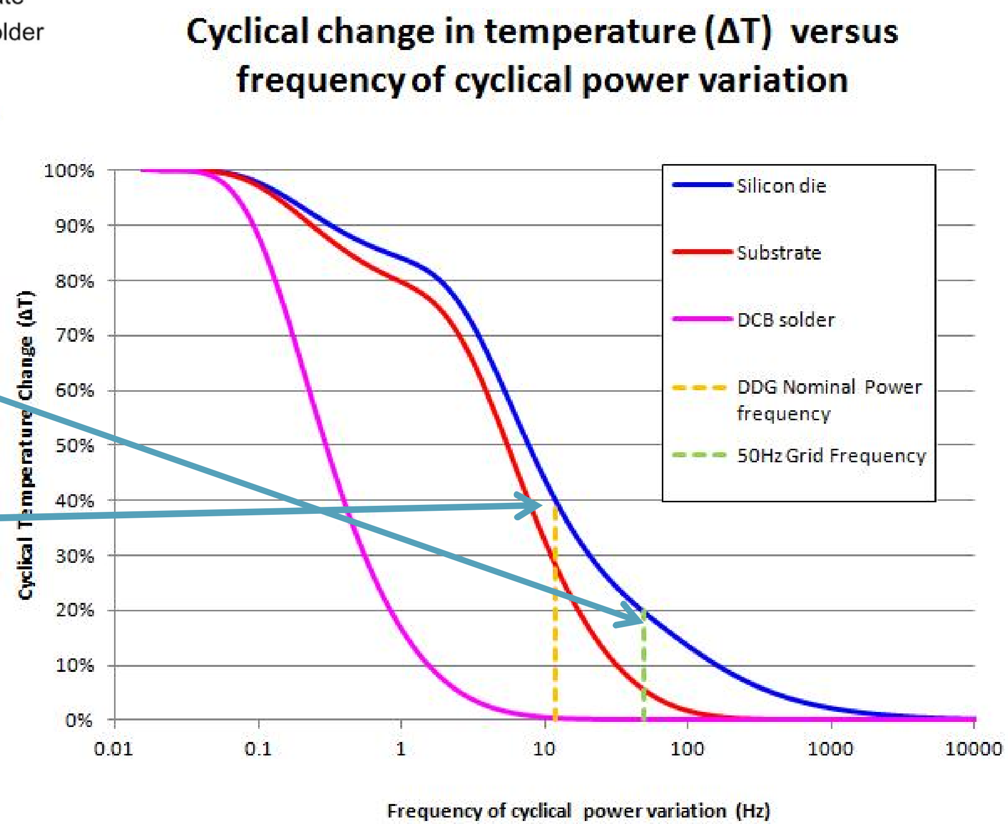

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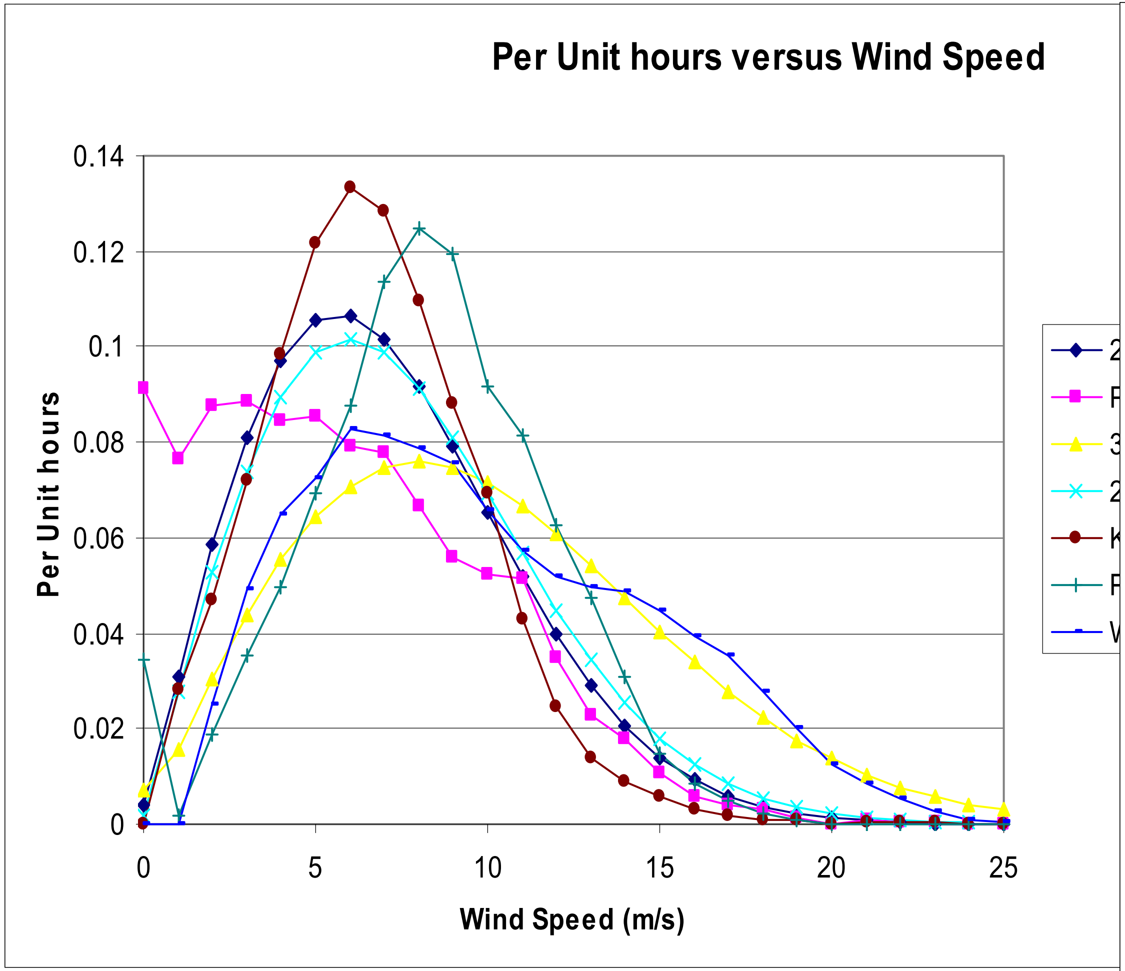
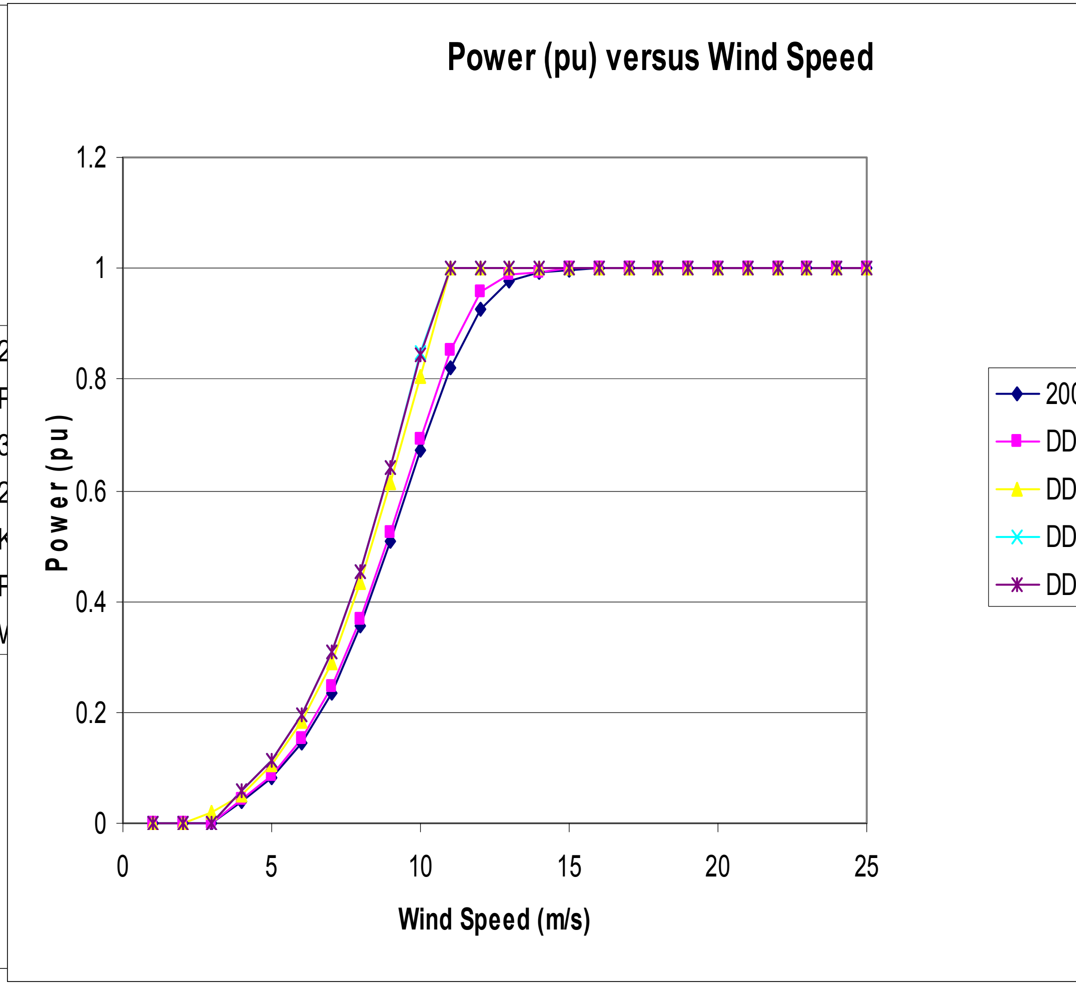
Mission Profile





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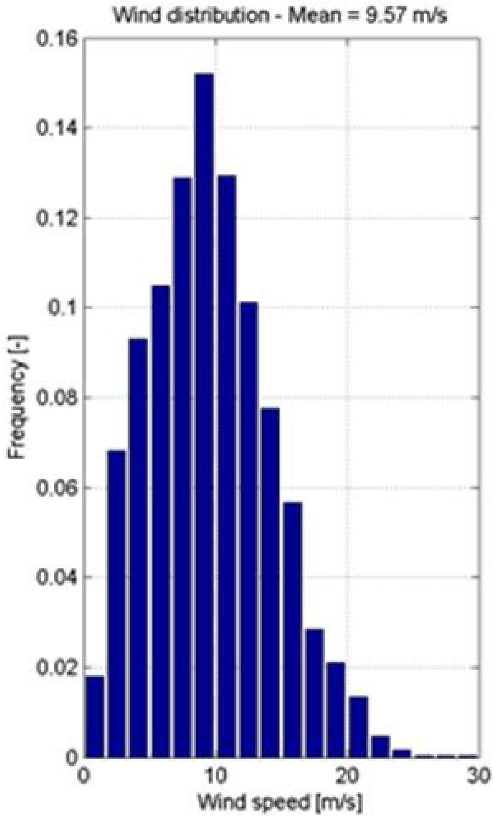
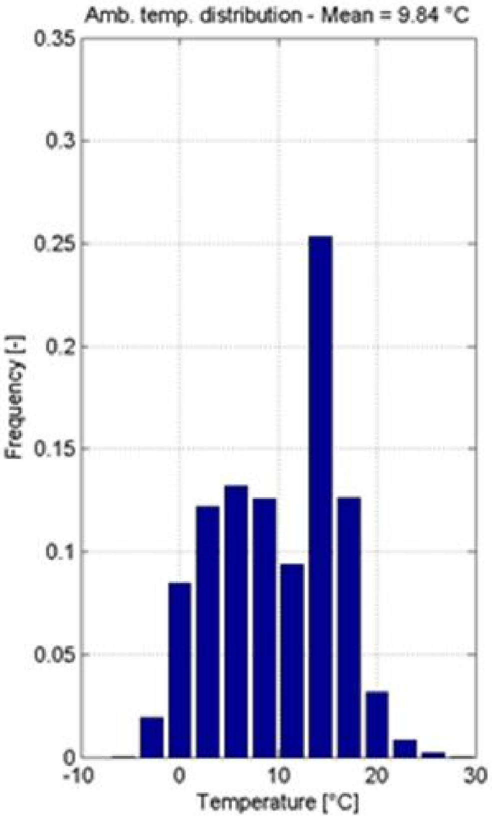
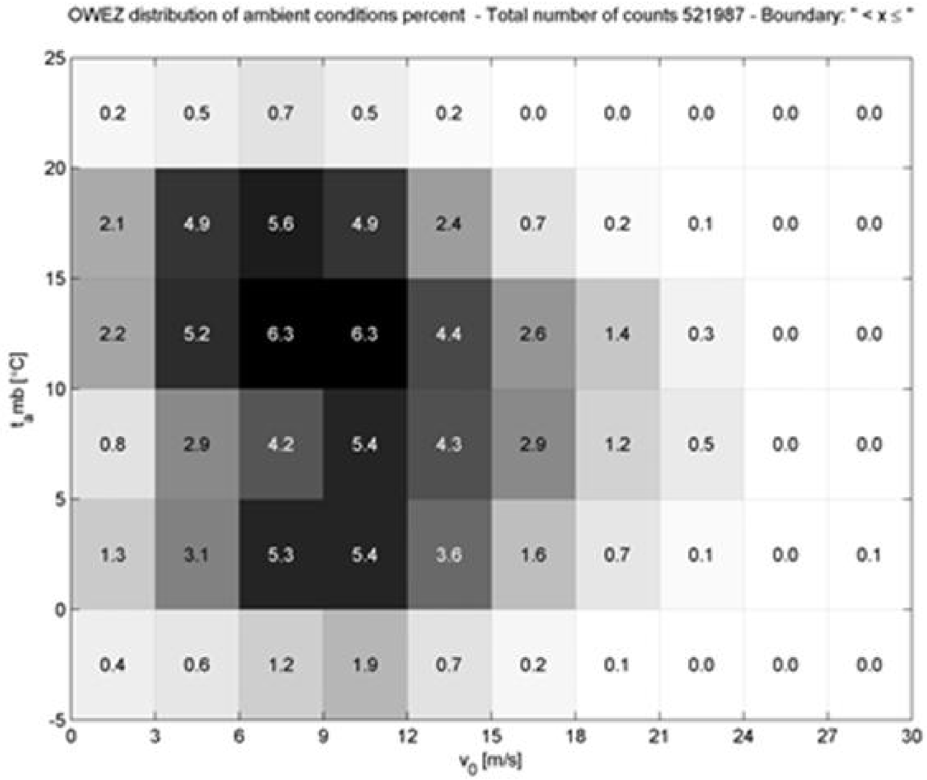
Weather Data input to Mission Profile calculation







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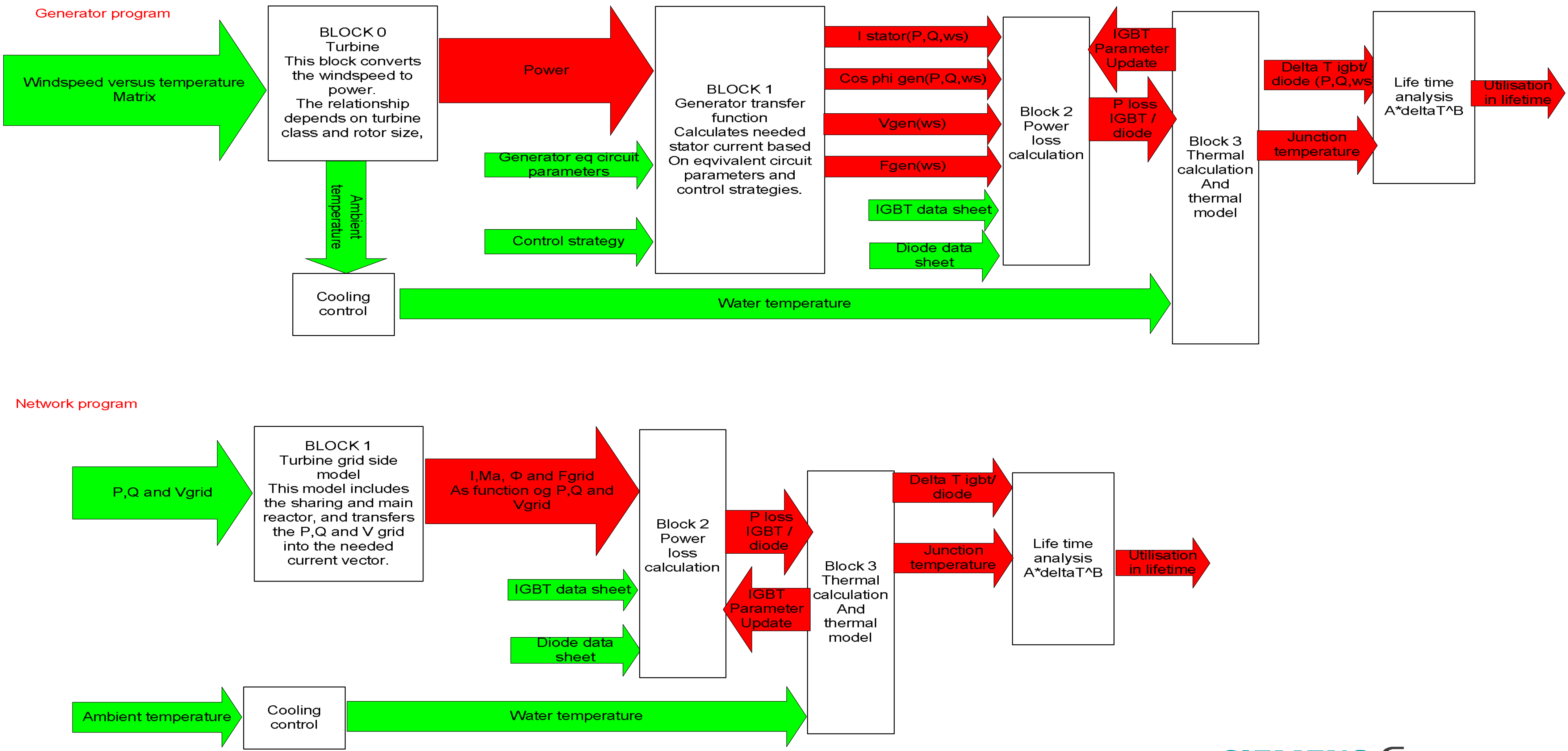
Calculation Process for IGBT/Diode Utilisation



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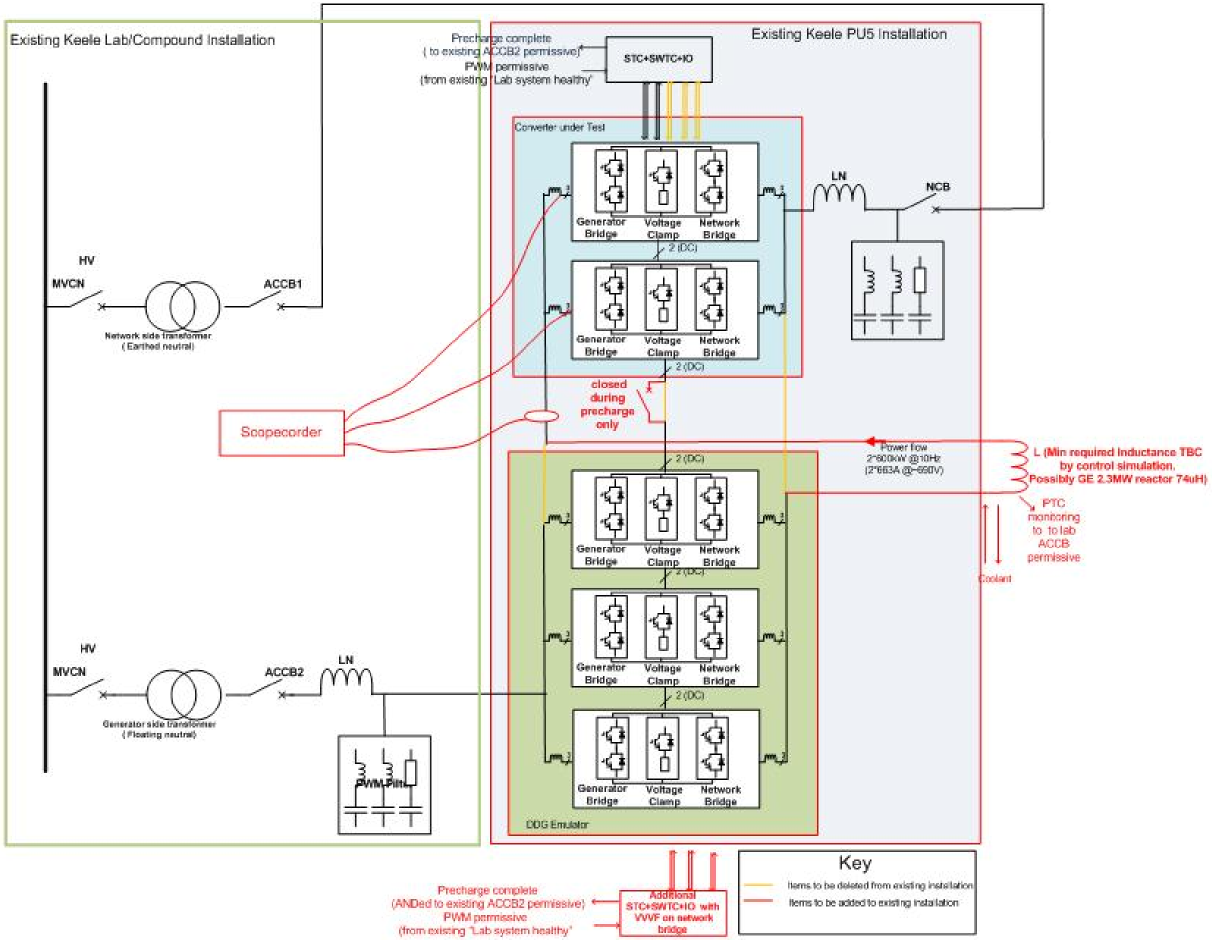
IGBT Accelerated Lifetime Testing



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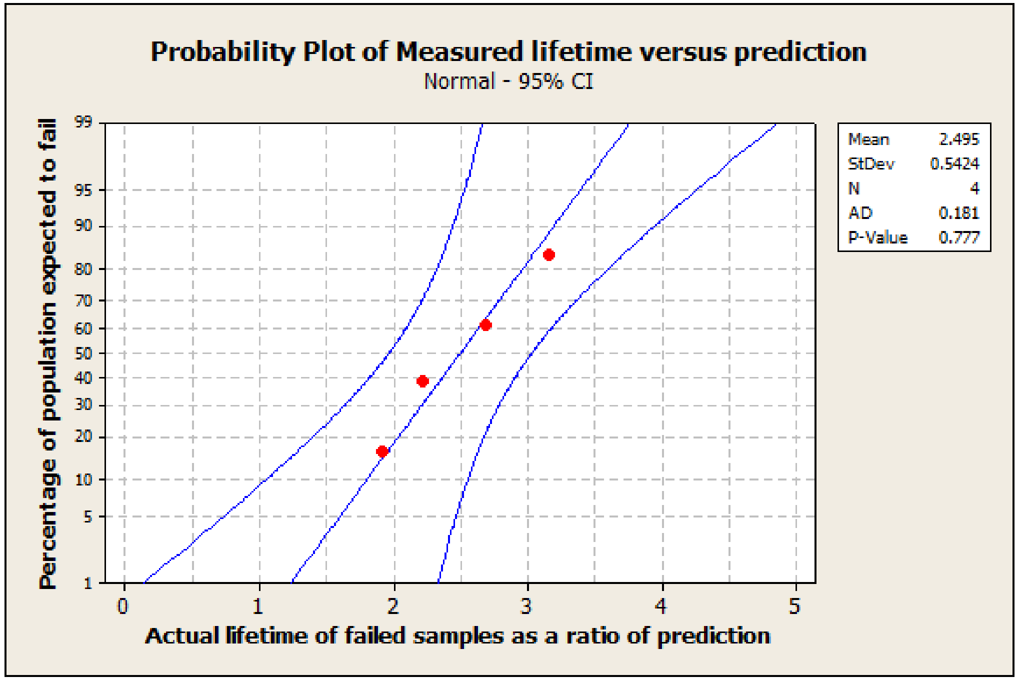
<u>Preliminary</u> Results for fastest acceleration test



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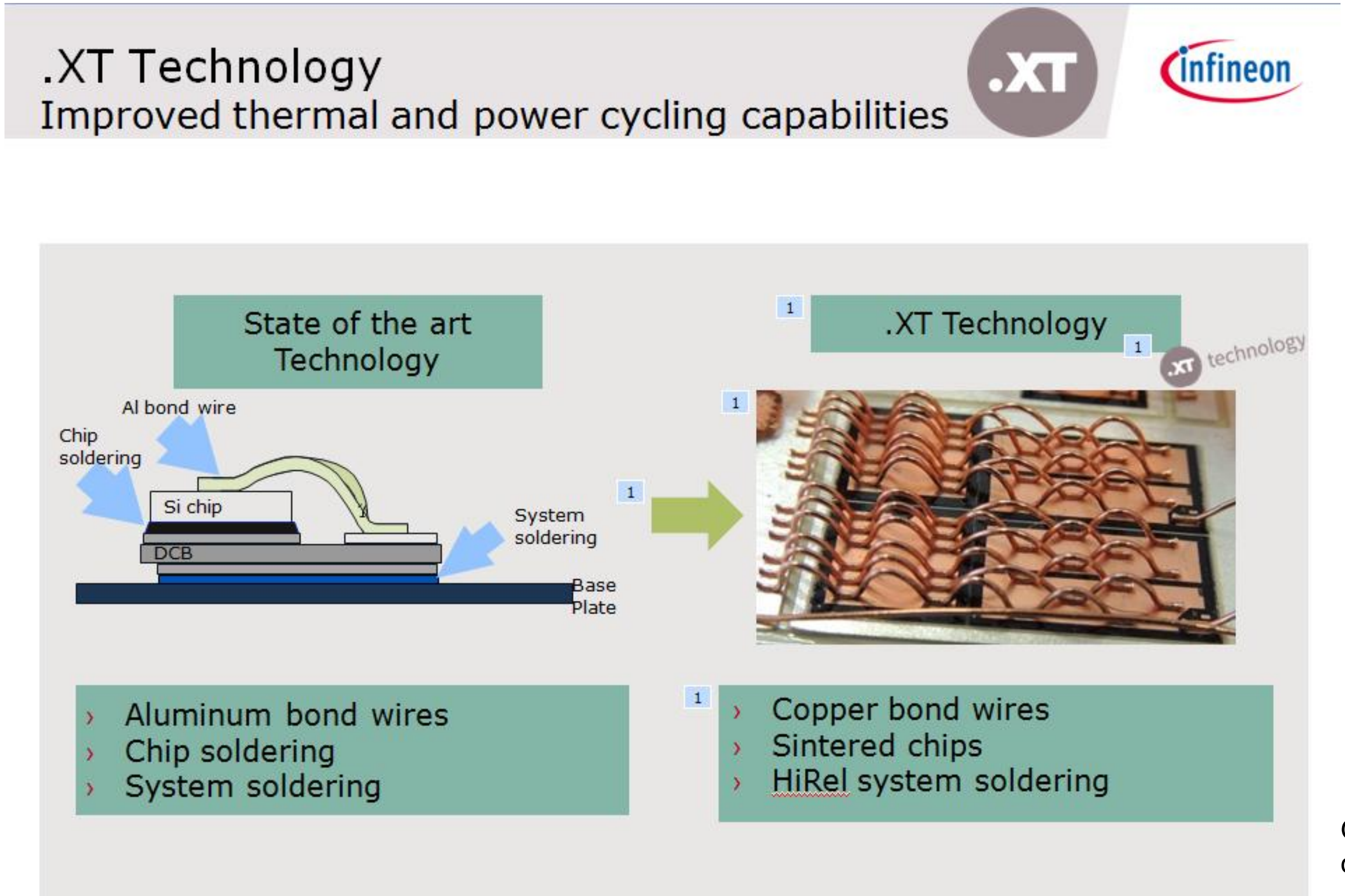
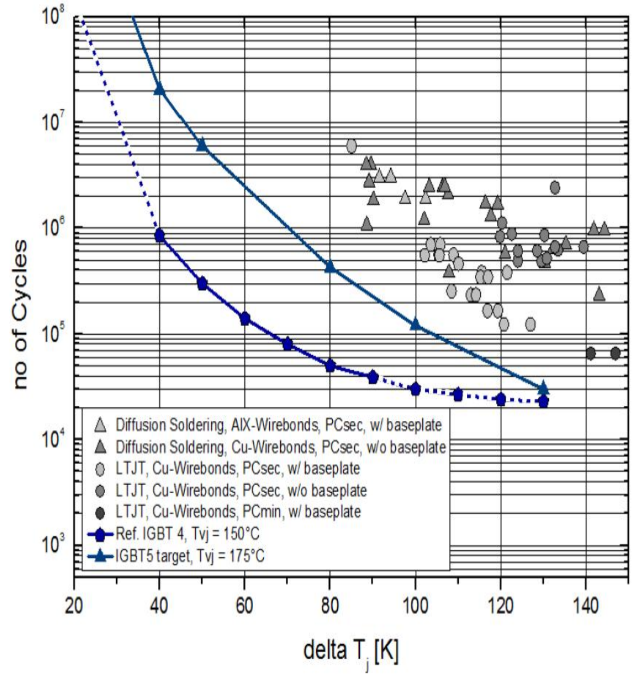
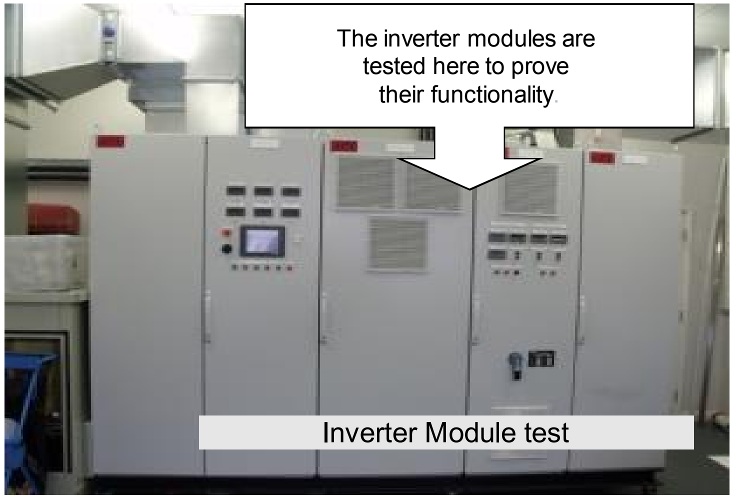
Next Generation

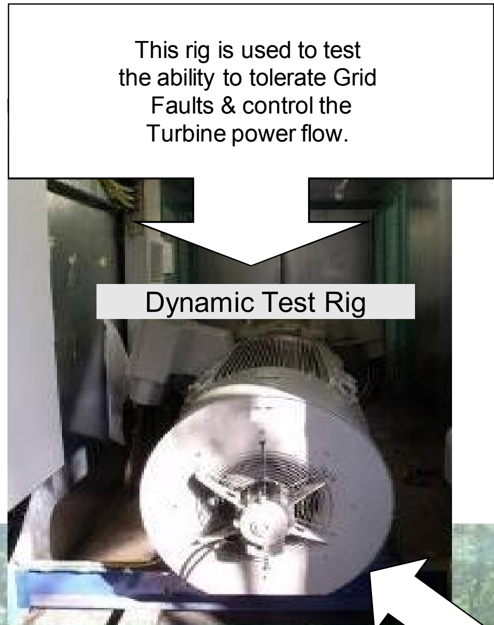


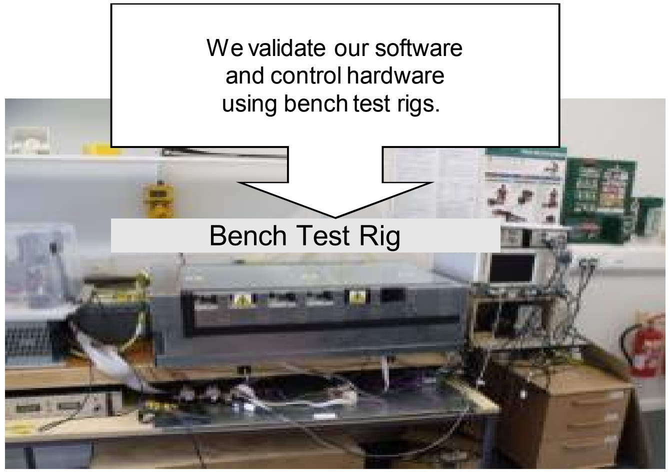


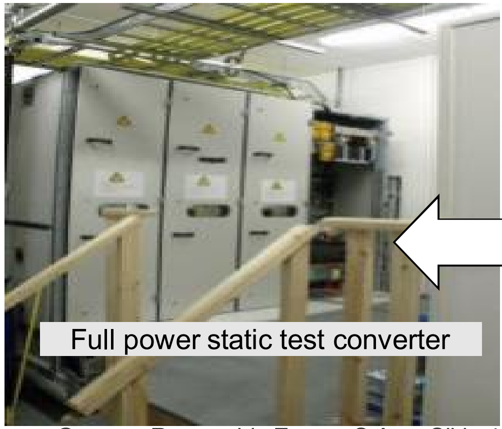
Other suppliers are also developing alternative competitive solutions to increase bond-wire lifetime

Test Facilities









We can run the Converter to Full power with this rig.

Wind/Renewable Industry Outlook & Challenges

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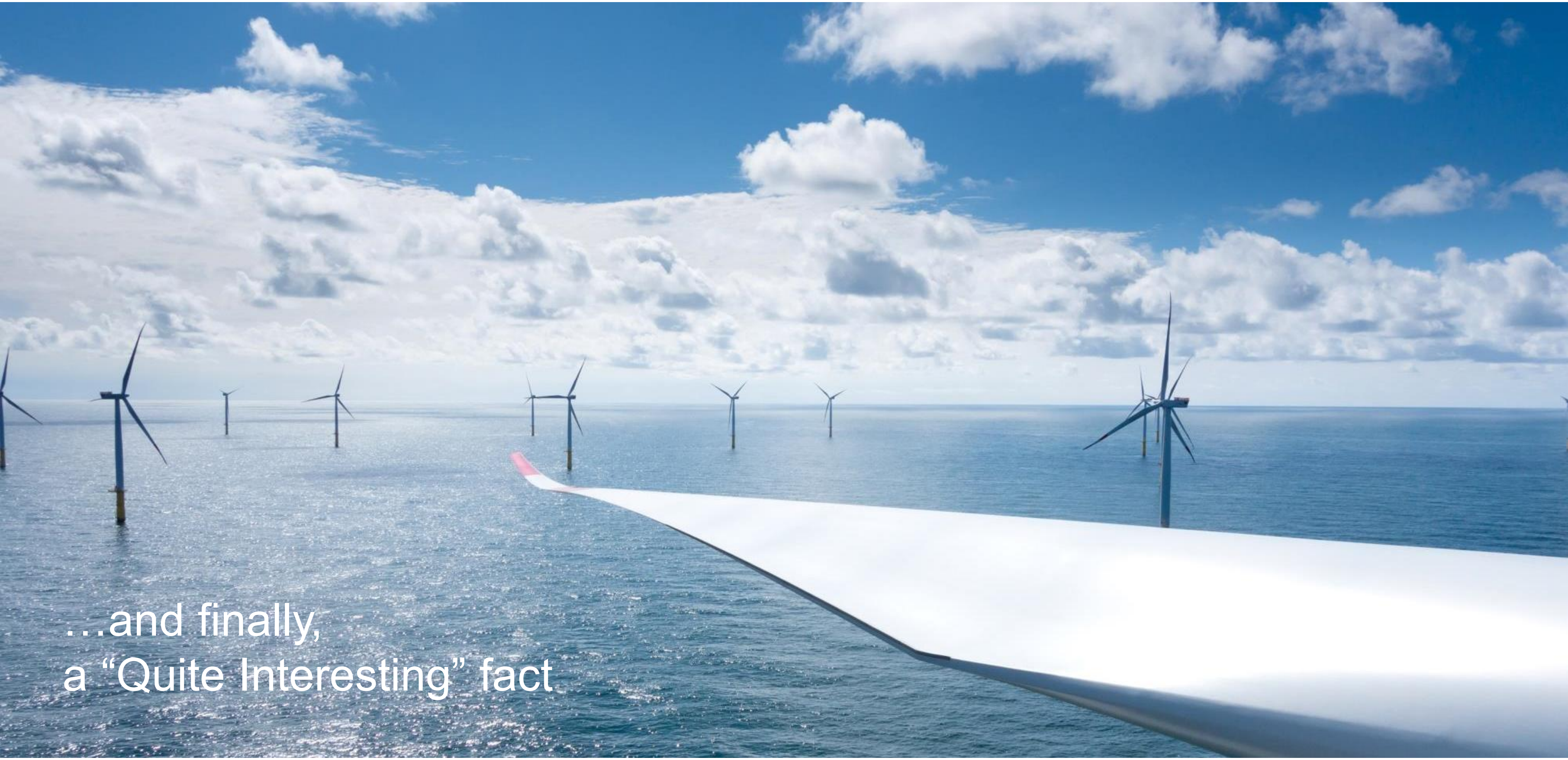
Wind/Renewable Industry Outlook &Challenges

Challenges – Electrical Drive Train Perspective

- Ratings increase of offshore WTG 6, 7, 8……+10MW and availability of suitable low cost, further increased reliability power converter solutions.
- How to bring down the costs of the drive train components.
- The cost and risk managements of new technology introductions.
- Support of the existing fleet and legacy products.
- How to address the effects on grid of displacing retired Synchronous Machine Generation.
- How to significantly improve electrical drive train efficiency and increase AEP.



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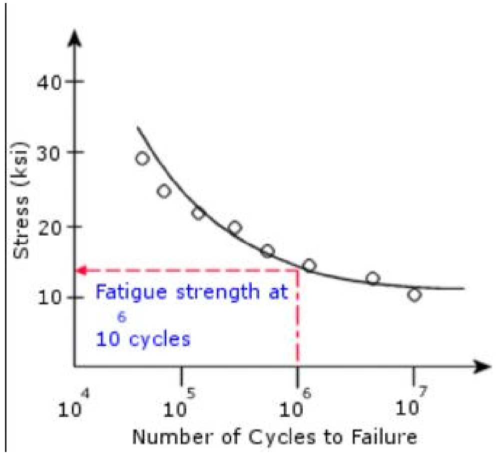
Why do you only see 3 bladed Horizontal Axis Wind Turbines these days!



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Questions

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