Challenges faced by the wind industry

Power System Balancing and Operation with Large Shares of Wind Power

Łukasz Kocewiak

Power System Transformation

Evolution of Power Systems

Yesterday, today, and tomorrow

DC distribution
1880s

Pump storage
1907

Synchronous
condenser
1950s

Grid connected
battery storage
2010s

Power electronic
virtual synchronous
machine

Conventional Power System

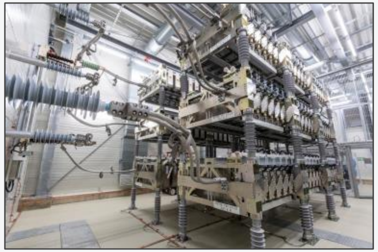
Modern Power System

Future Power System

AC synchronous
machine
1870s

HVDC
1954

Static Synchronous
Compensator
1991

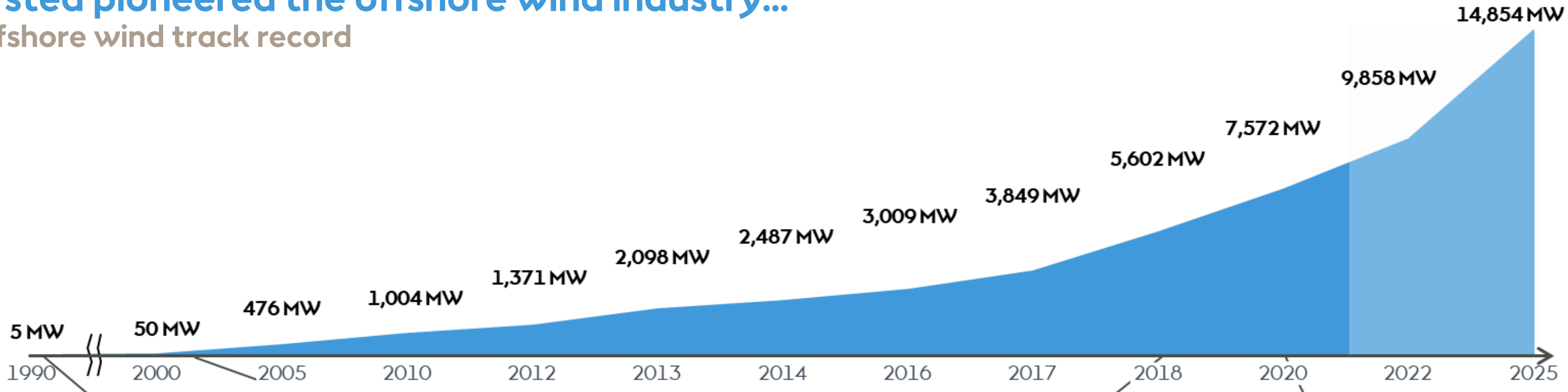


Power electronic
based power system

The first three-phase synchronous machine built by Friedrich August Haselwander in 1887 (Photo: Deutsches Museum, Munich)

Ørsted pioneered the offshore wind industry…

Offshore wind track record



Pre-2009: Project by project

Post-2009: Industrialised approach to planning and execution of offshore wind projects

Selected projects

Vindeby

First offshore wind farm in the world

5 MW

Turbine capacity	0.45 MW
Nr. of turbines	11
Rotor diameter	35 m
Distance to shore	1.8 km

Horns Rev 1

First large scale offshore wind farm in the world

160 MW

Turbine capacity	2 MW
Nr. of turbines	80
Rotor diameter	80 m
Distance to shore	18 km

Walney Extension

The first offshore wind farm to deploy two different wind turbines

659 MW

Turbine capacity	7-8.25 MW
Nr. of turbines	87
Rotor diameter	154-164 m
Distance to shore	19 km

Hornsea 1

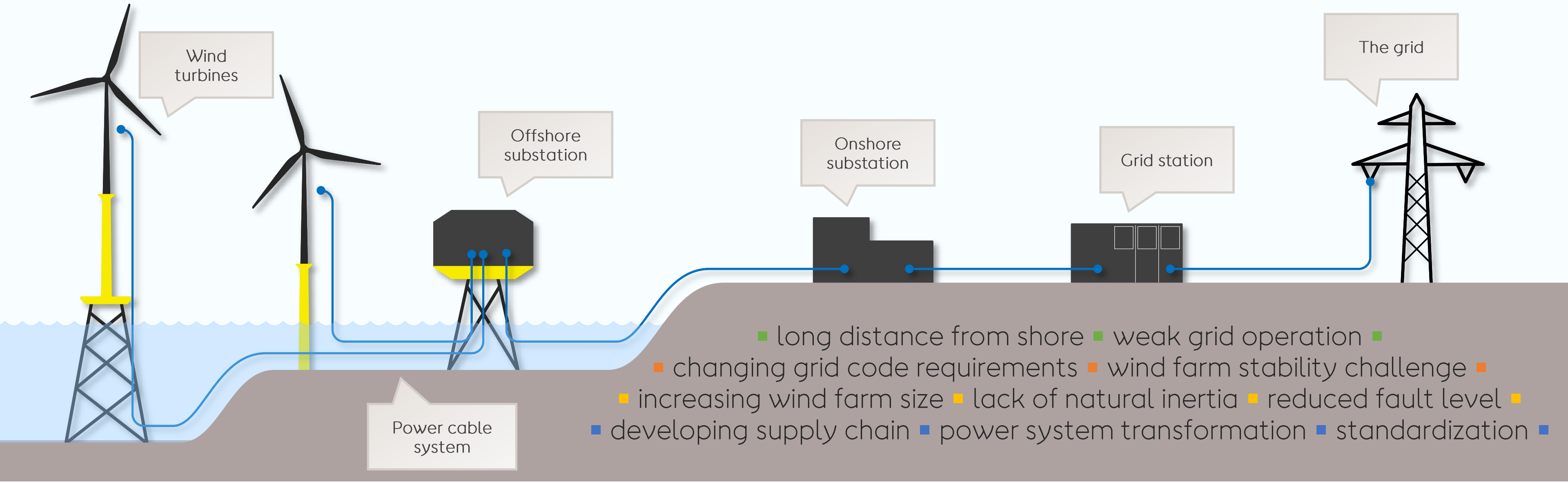
The world's largest operation offshore wind farm

1,218 MW

Turbine capacity	7 MW
Nr. of turbines	174
Rotor diameter	154 m
Distance to shore	120 km

Offshore Wind Farm Electrical System

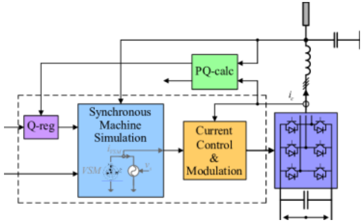
Increasing complexity



🟩 long distance from shore 🟩 weak grid operation 🟩
🟧 changing grid code requirements 🟧 wind farm stability challenge 🟧
🟨 increasing wind farm size 🟨 lack of natural inertia 🟨 reduced fault level 🟨
🟦 developing supply chain 🟦 power system transformation 🟦 standardization 🟦

Energy Storage

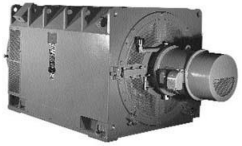
Virtual Synchronous Machine



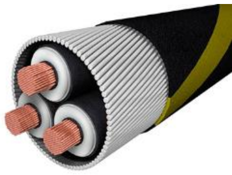
Dynamic Reactive Power Control

Active Filtering and Damping

Synchronous Condenser



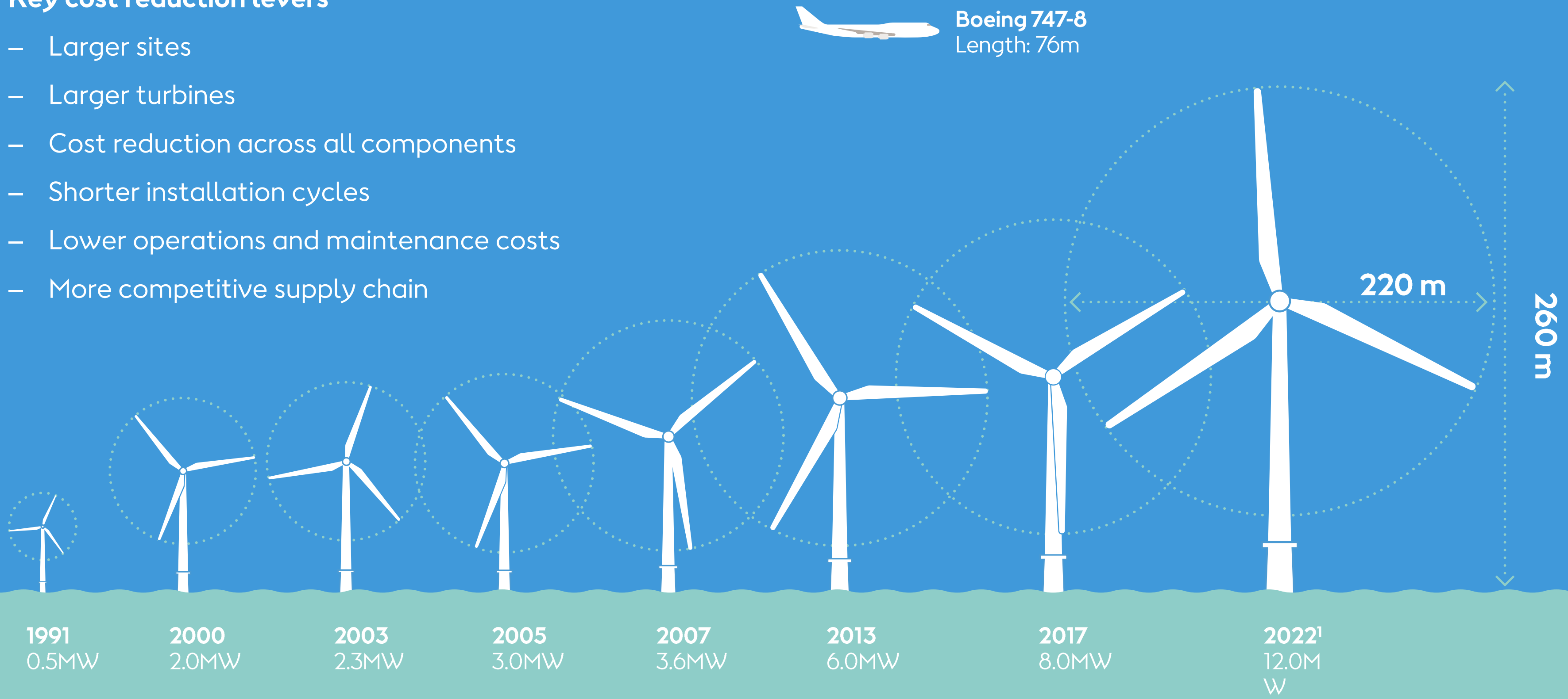
Power Cable



Scale and continuous innovation have driven down the cost of offshore wind

Key cost reduction levers

- Larger sites
- Larger turbines
- Cost reduction across all components
- Shorter installation cycles
- Lower operations and maintenance costs
- More competitive supply chain



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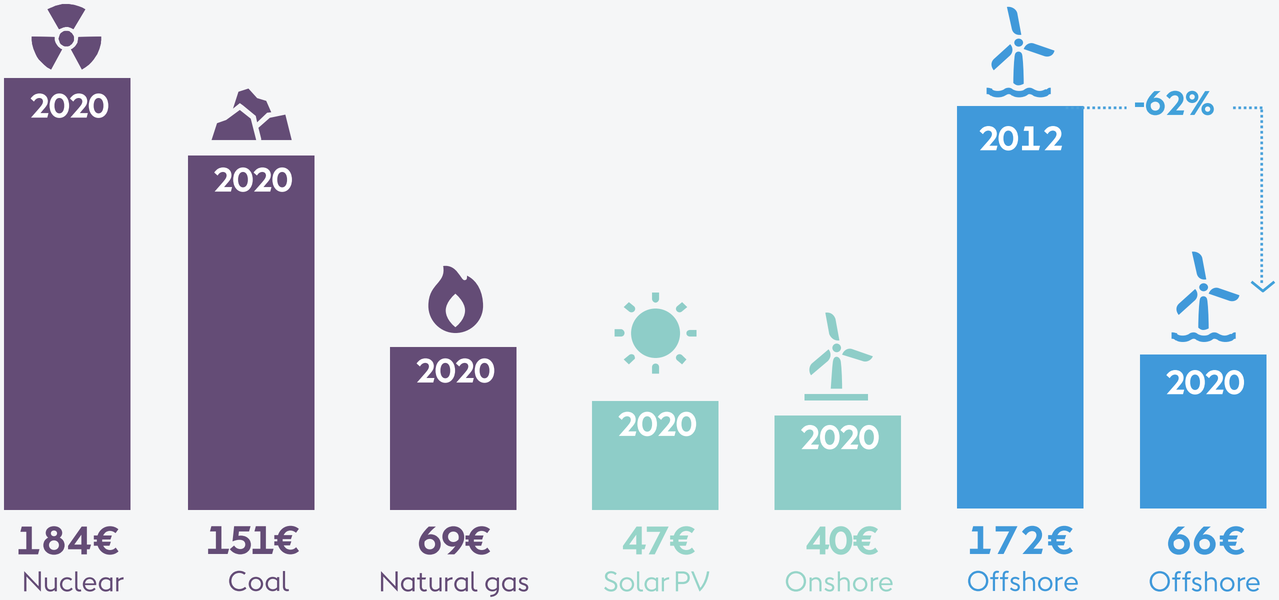
[1] Expected year of commissioning.

Today offshore wind is competitive with fossil fuels

EUR/MWh, 2021 prices, Northwest Europe



Source: Bloomberg NEF – 2H 2020 LCOE Update, current LCOE and Ørsted calculation. Onshore wind: average of DE, NL and UK mid-scenarios. Solar PV, Natural Gas: average of DE, UK mid-scenarios. Coal: DE mid-scenario. Nuclear: UK mid-scenario. Offshore wind 2020: average of DK, NL and UK mid-scenarios. Offshore wind 2012: generic offshore wind, Northwest Europe, FID 2012. In 2012 our goal was to reduce offshore wind costs to EUR 100 per MWh in 2020. EUR:USD: 0.81, YoY inflation 2019-2020: 1.5%.

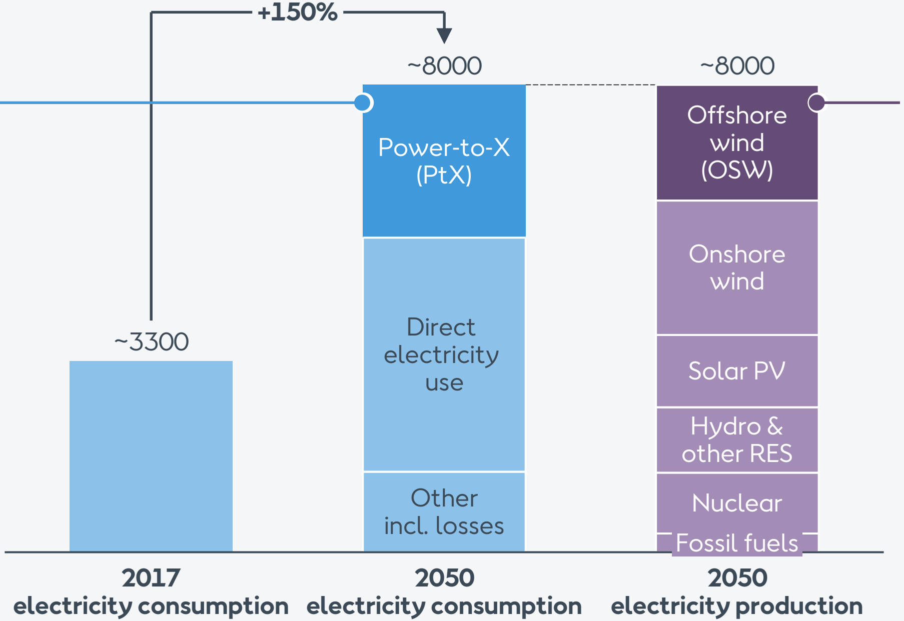
Europe needs to build large amounts of new renewable electricity capacity
to reach net-zero by 2050

Full decarbonisation requires electrification which will increase electricity demand by 150%

EU electricity production and consumption by source[1], TWh

Hydrogen is the bridge between renewable electricity and hard-to-decarbonise sectors

EU has set target of 40 GW of electrolyser capacity by 2030, equal to around 200 TWh of electricity consumption



EU needs 450 GW of offshore wind by 2050 to meet increased demand for electricity

Denmark has some of the best offshore wind sites in Europe, with potential for at least 40 GW[2]

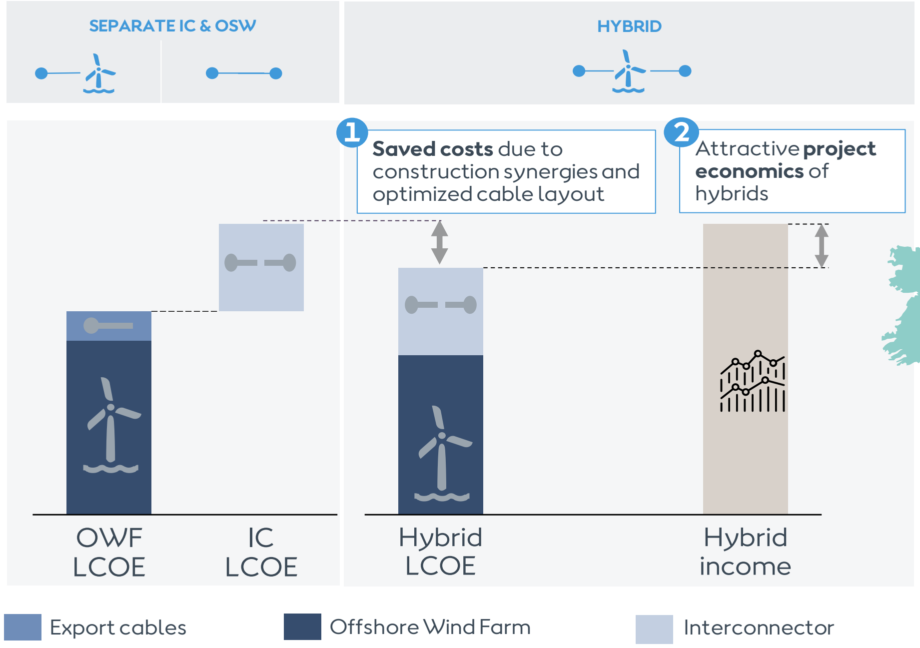
Source 1: EU Commission long term strategy (1.5 tech scenario).

Source 2: Offshore wind and infrastructure, EA Energianalyse for Ørsted, February 2020

To unlock the full potential of offshore wind,

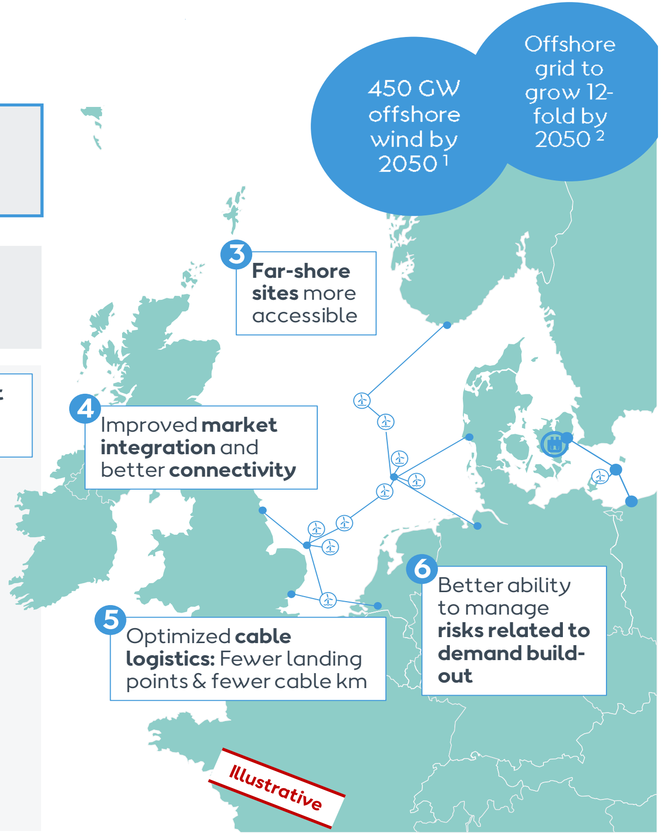
we need to rethink offshore transmission

A **hybrid asset** is an offshore wind farm connected to at least two markets, creating the opportunity for dual use of the transmission line.



1 **Saved costs** due to construction synergies and optimized cable layout

2 Attractive **project economics** of hybrids



450 GW offshore wind by 2050 [1]

Offshore grid to grow 12-fold by 2050 [2]

3 **Far-shore sites** more accessible

4 Improved **market integration** and better **connectivity**

5 Optimized **cable logistics:** Fewer landing points & fewer cable km

6 Better ability to manage **risks related to demand build-out**

1: EC Commission long term strategy (1,5 tech scenario)

2: Offshore wind and infrastructure, EA Energianalyse for Ørsted, February 2020. The metric GWx1,000km is chosen to illustrate not only the length but also capacity.

Challenge #1
System Stability

Power system transformation

Changes in fault level and natural inertia

Short-circuit level

- The decline in short circuit level will present risks for protection and PLL operation
- Increasing short-circuit level at transmission will be more effective that at distribution to resolve transmission issues
- Existing inverter-based technologies are limited in providing high levels of fault current

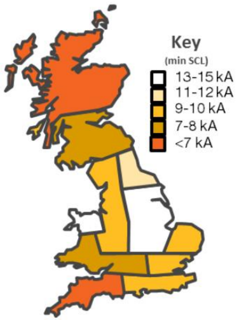
Inertia response

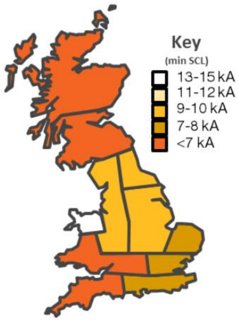
- The key service to be provided is inertia, which helps to keep the electricity system running at the right frequency
- Has traditionally been provided by using the kinetic energy in the spinning parts of large generators

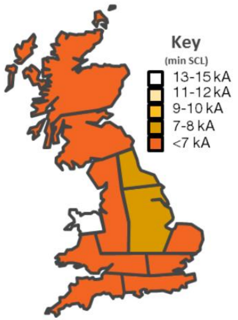
$$\text{Short circuit level (MVA)} = \sqrt{3} * \text{Rated voltage (kV)} * \text{Fault current(kA)}$$

$$\text{Inertia} = H \times S_{rating}$$

$$H = \frac{\Delta P\, f_0}{2\, S_{rating} RoCoF}$$


2020

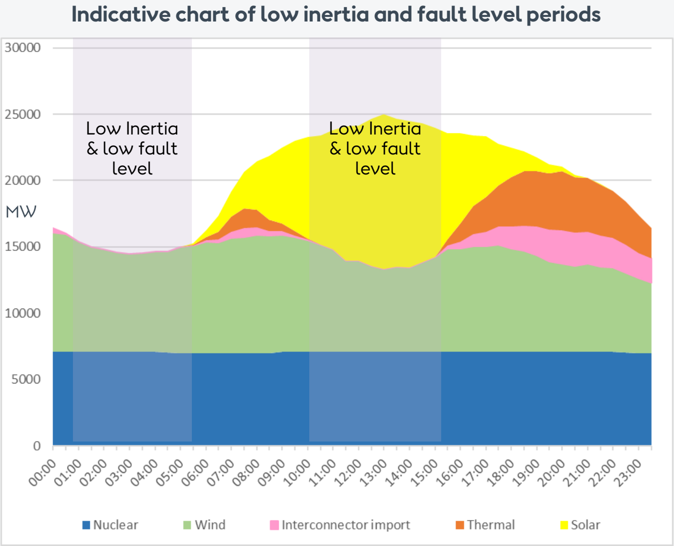

2025


2030

Source 1: National Grid ESO System Operability Framework – Impact of declining short circuit levels
Source 2: National Grid ESO System Operability Framework – Whole system short circuit levels
Source 3: National Grid ESO Our new approach to inertia and other stability services

Ancillary services to enhance stability

Inertia and fault infeed



INERTIA

Synthetic inertia can be provided by grid-connected converters, e.g. wind turbines, battery energy storage systems, static synchronous condensers.

Preferably storage is needed to avoid recovery time in wind turbines. Small storage below 1GJ is typically enough to deliver inertia response.

FAULT INFEED

Typically converters are rated to provide the maximum **fault current** at rated MVA plus 10% (whereas 5x MVA for synchronous generators).

Higher fault current rated converters could be developed and installed in future power systems.

Challenge #2
System Resilience

Blackout

Largest outages in history

1

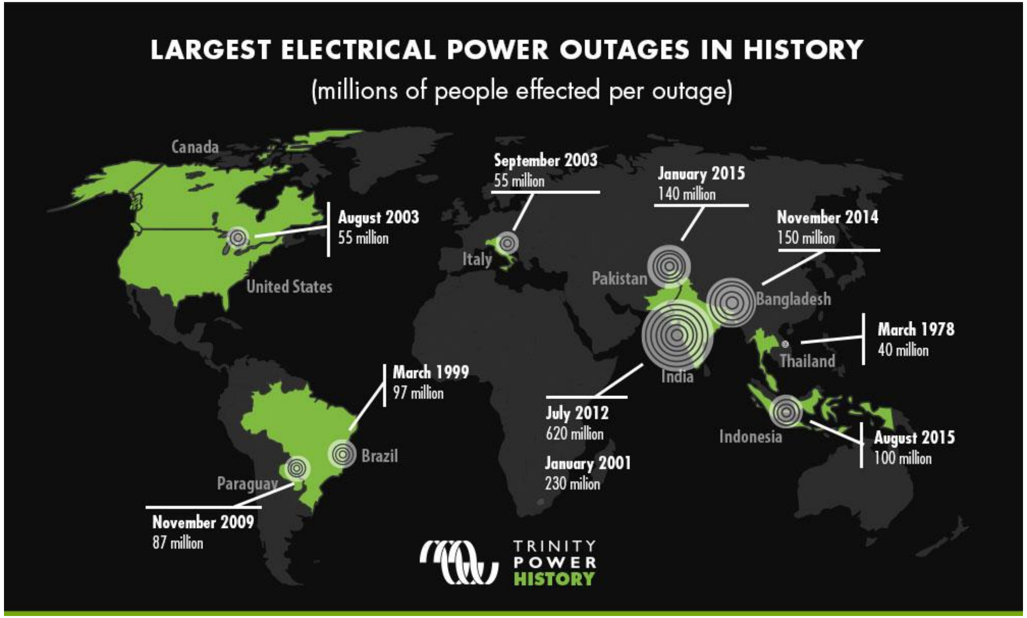
- July 2012, **India**: The biggest power outage in India to date, and potentially the biggest power failure in the world, ever, left half of India-upwards of 620 million people-without power.

2

- January 2001, **India**: 230 million people lost power due to a fault in the transmission system in one state, causing cascading failure throughout the northern Indian region.

3

- November 2014, **Bangladesh**: A nationwide power outage affected 150 million people for half a day, traced to the failure of a power transmission line from India into Bangladesh.



LARGEST ELECTRICAL POWER OUTAGES IN HISTORY

(millions of people effected per outage)

Source: https://www.trinitypower.com/ten-biggest-electrical-power-outages-of-all-time/

Power system resilience

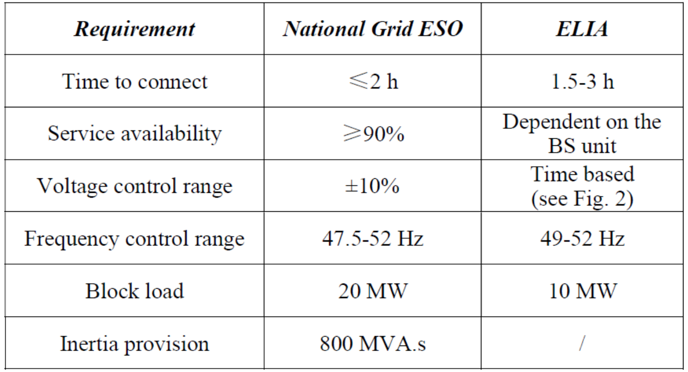
Can wind farms contribute to system restoration?

Green Start from wind farms

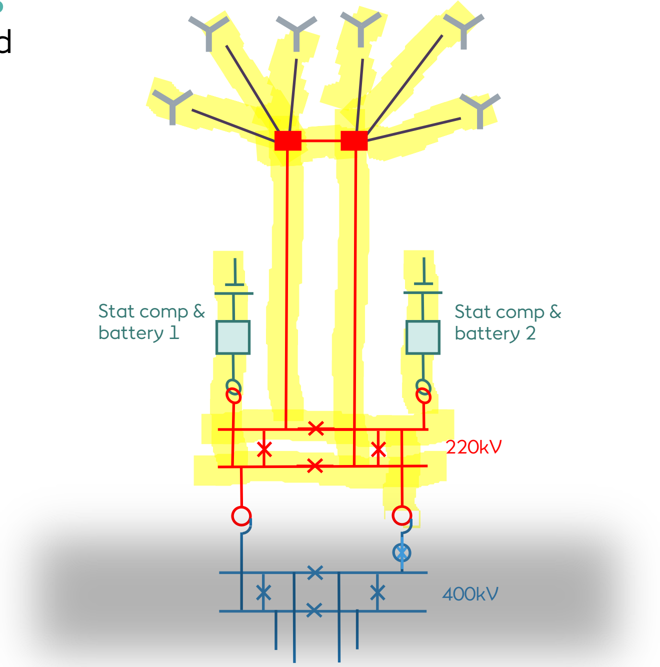
- The wind farm output power is dependent on wind conditions
- Grid restoration can be provided only when wind is blowing
- Does wind farm need to energize its own assets or also onshore transmission system?

Black start from wind farms

- Incorporating a BESS into the wind farm design may enable black start from wind farms
- STATCOM combined with BESS would provide uninterrupted grid forming capabilities



Requirement	*National Grid ESO*	*ELIA*
Time to connect	⩽2 h	1.5-3 h
Service availability	⩾90%	Dependent on the BS unit
Voltage control range	±10%	Time based (see Fig. 2)
Frequency control range	47.5-52 Hz	49-52 Hz
Block load	20 MW	10 MW
Inertia provision	800 MVA.s	/



D. Pagnani, Ł. Kocewiak, J. Hjerrild, F. Blaabjerg, C. L. Bak, „*Overview of Black Start Provision by Offshore Wind Farms*," in Proceedings of IECON 2020: 46th Annual Conference of the IEEE Industrial Electronics Society, IEEE Press.

System Design

Electrical transmission design

Studies to address growing complexity

Steady state analyses

- Load flow – active power flow, reactive power balance, voltages and currents limits, grid code compliance, e.g. reactive power control ranges
- Fault analyses – short-circuit current for different faults, components withstand capabilities

Dynamic analyses

- Transient stability – wind farm ability to ride through faults, wind farm response in abnormal conditions
- Dynamic analyses – verify the performance of control functions, e.g. voltage control, reactive power control, active power control, frequency control

Power quality

- Harmonic analyses – electromagnetic compatibility within wind farm system, disturbances within limits
- Harmonic filter design – components dimensioning, grid code compliance, resonance damping

Electromagnetic transient analyses

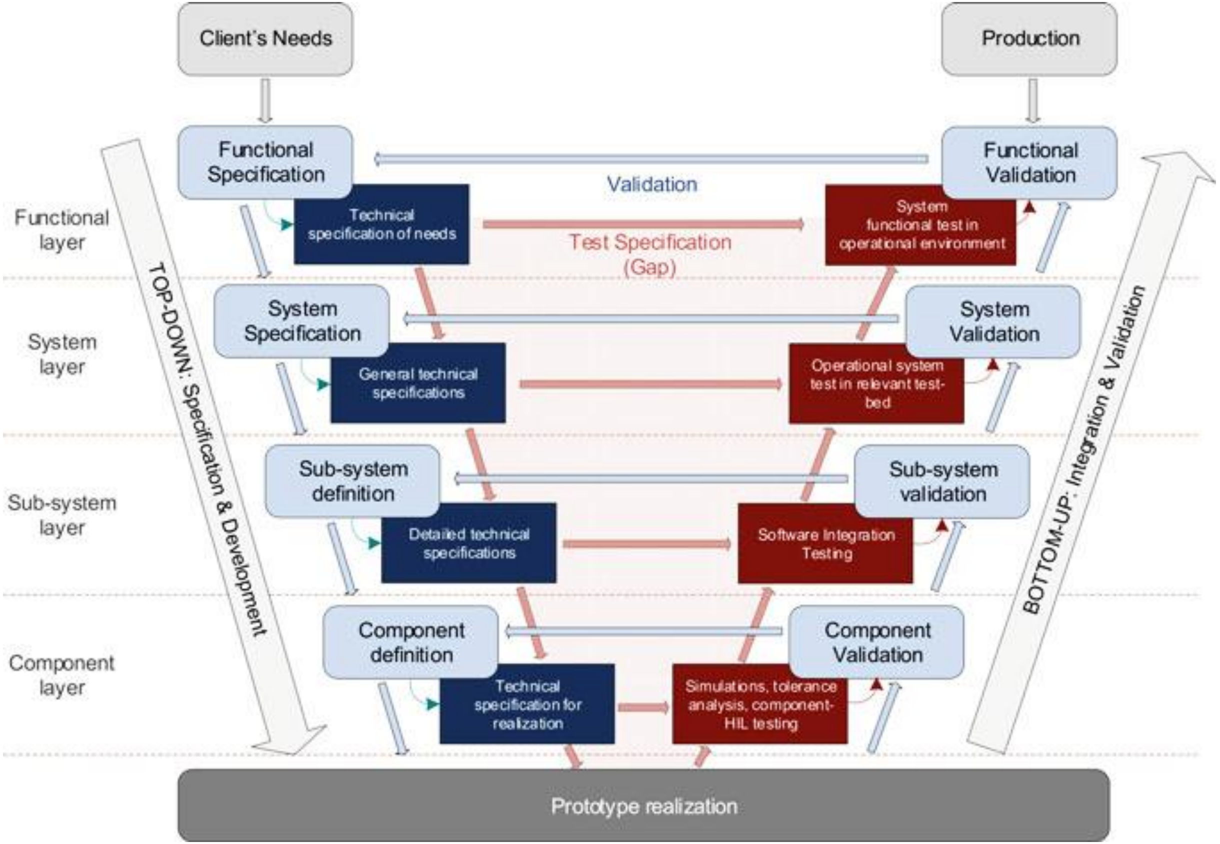
- Energization – grid code compliance, e.g. reactive power and voltage jumps, inrush current, voltage fluctuations, insulation coordination
- Detailed dynamic studies – wind farm behavior in case of faults, e.g. low- and high-voltage ride through, load rejection

Control stability

- Small-signal stability – interaction with passive network and other active elements, e.g. impedance-base or eigenvalue-based analysis
- Large-signal stability – stability evaluation during faults, phase jumps, voltage dips

Higher quality in system design and validation

Need for testing



Thomas Strasser, Erik C. W. de Jong, Maria Sosnina, „European Guide to Power System Testing: *The ERIGrid Holistic Approach for Evaluating Complex Smart Grid Configurations*," Springer International Publishing, 2020.

Converter model quality to perform studies

Wind turbine model validation

CLASS 1. SIMULATED/CALCULATED BASED ON WT DESIGN

- Harmonic model development based on simulations/calculations or software in the loop (SIL) studies incorporating actual design of a WT taking into account precise product specification, e.g. harmonic model developed based on WT design documentation and detailed models (e.g. EMTP-based, C-code from the control software, etc.).

CLASS 2. VERIFIED BY LAB

- Harmonic model development based on control hardware in the loop (CHIL) and/or power hardware in the loop (PHIL) studies in a controlled environment. The test will incorporate the actual WT components such as the control or/and converter systems.

CLASS 3. VERIFIED BY FIELD MEASUREMENTS

- Harmonic model is verified by measurements and model outputs are verified by measurement of the WT. The measurements can be done either at the test rig/bench or in the field, e.g. harmonic model verified by measurements or a prototype WT or at the test stand.

Source: IEC TR 61400-21-3:2019, "*Wind Energy Generation Systems – Part 21-3: Wind turbine harmonic model and its applications*".

Area #1
Power Quality

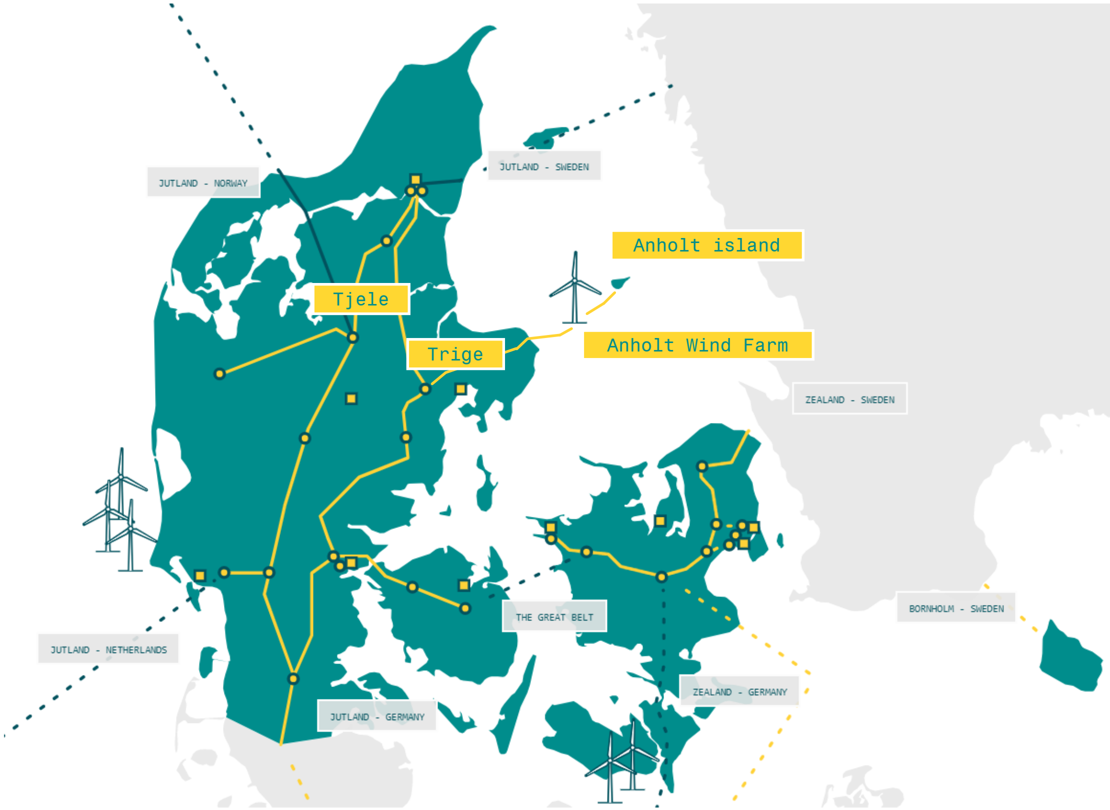
Example from Anholt Offshore Wind Farm in Denmark

Voltage quality problems on Anholt island

> The problem arises because naturally occurring **background noise** in the Jutland-Funen electricity transmission network is **amplified along the Anholt cable**. It is an unfortunate coincidence of the type of background noise, length of the Anholt cable and electrical characteristics.

> Both companies and the private sector [on Anholt island] have experienced **problems with various electrical appliances**, among others. electricity-saving bulbs, fluorescent lamps and appliances have been affected.

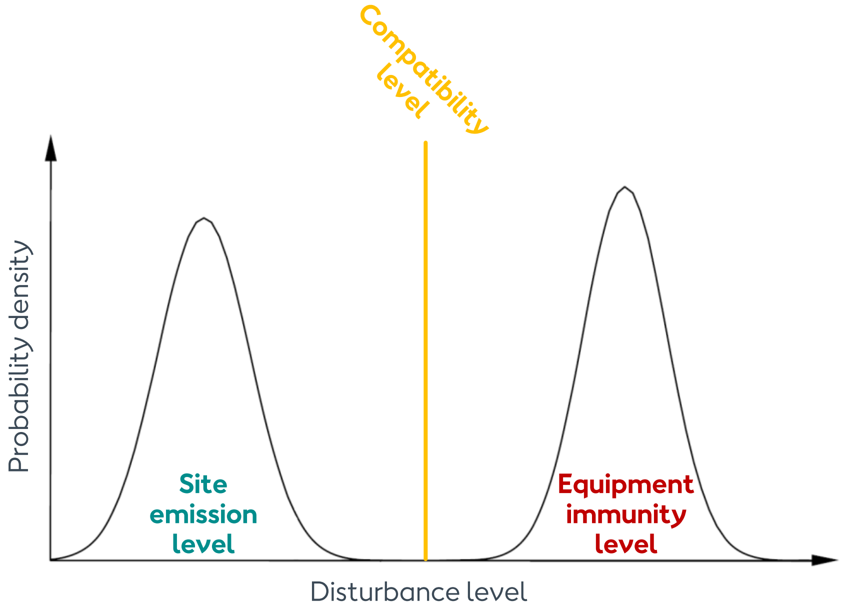
> The **[harmonic] filter** must ensure the correct voltage quality, so that electricity consumers at Anholt [island] will not in the future experience the nuisance they have been affected from time to time since the cable was put into operation.



Source: „Anholt forsynes igen fra øens generatorer", [Online] https://energinet.dk/Om-nyheder/Nyheder/2017/04/25/Anholt-forsynes-igen-fra-oens-generatorer

Electromagnetic compatibility in power systems

Harmonic planning and compatibility levels

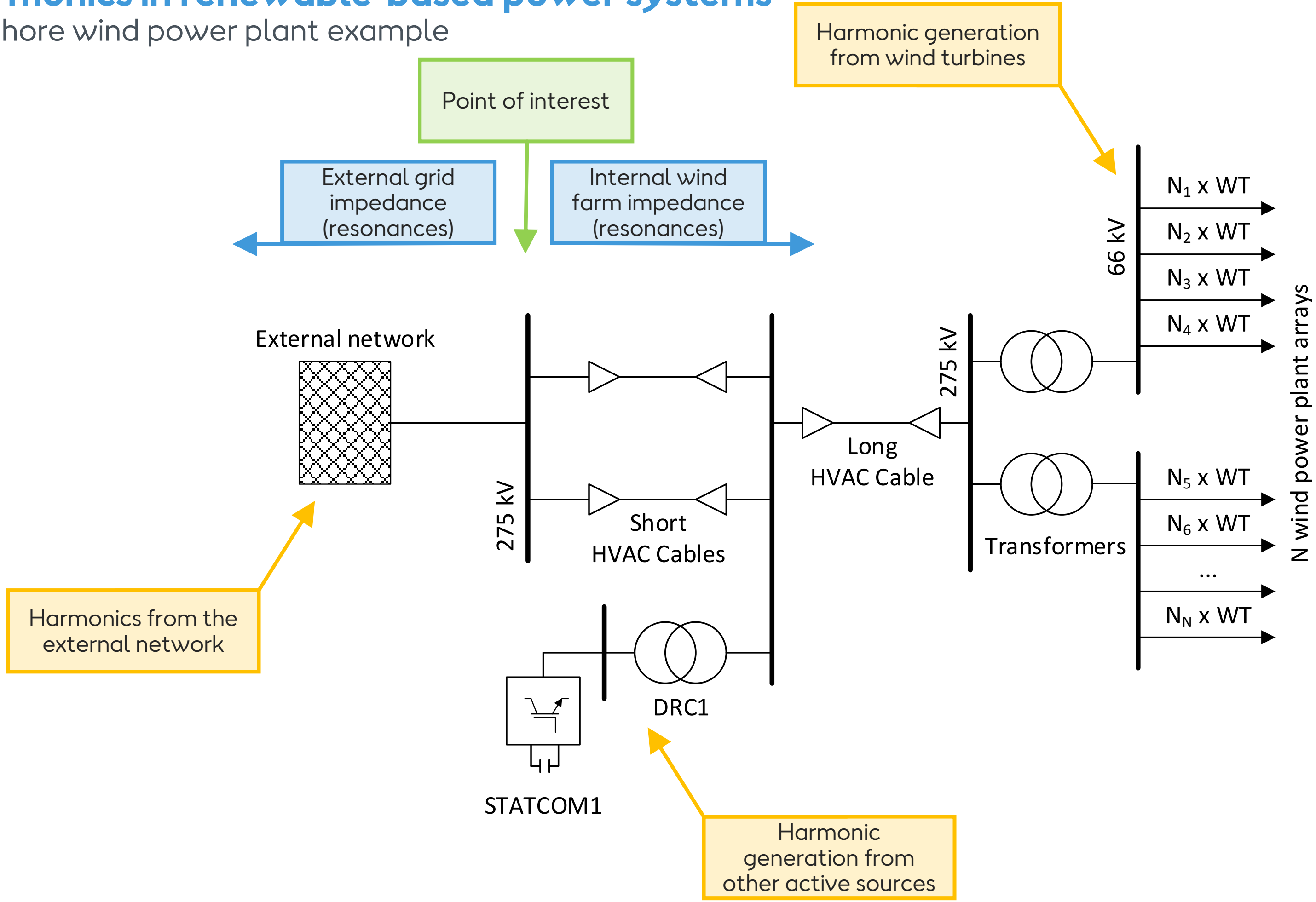


- **(electromagnetic) compatibility level:** specified electromagnetic disturbance level used as a reference level in a specified environment for co-ordination in the setting of emission and immunity limits
- **immunity level:** the maximum level of a given electromagnetic disturbance on a particular device, equipment or system for which it remains capable of operating with a declared degree of performance
- **emission level:** level of a given electromagnetic disturbance emitted from a particular device, equipment, system or disturbing installation as a whole, assessed and measured in a specified manner

Source: IEC TR 61000-3-6:2008, "Electromagnetic compatibility (EMC) – Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems".

Harmonics in renewable-based power systems

Offshore wind power plant example



Point of interest

External grid impedance (resonances)

Internal wind farm impedance (resonances)

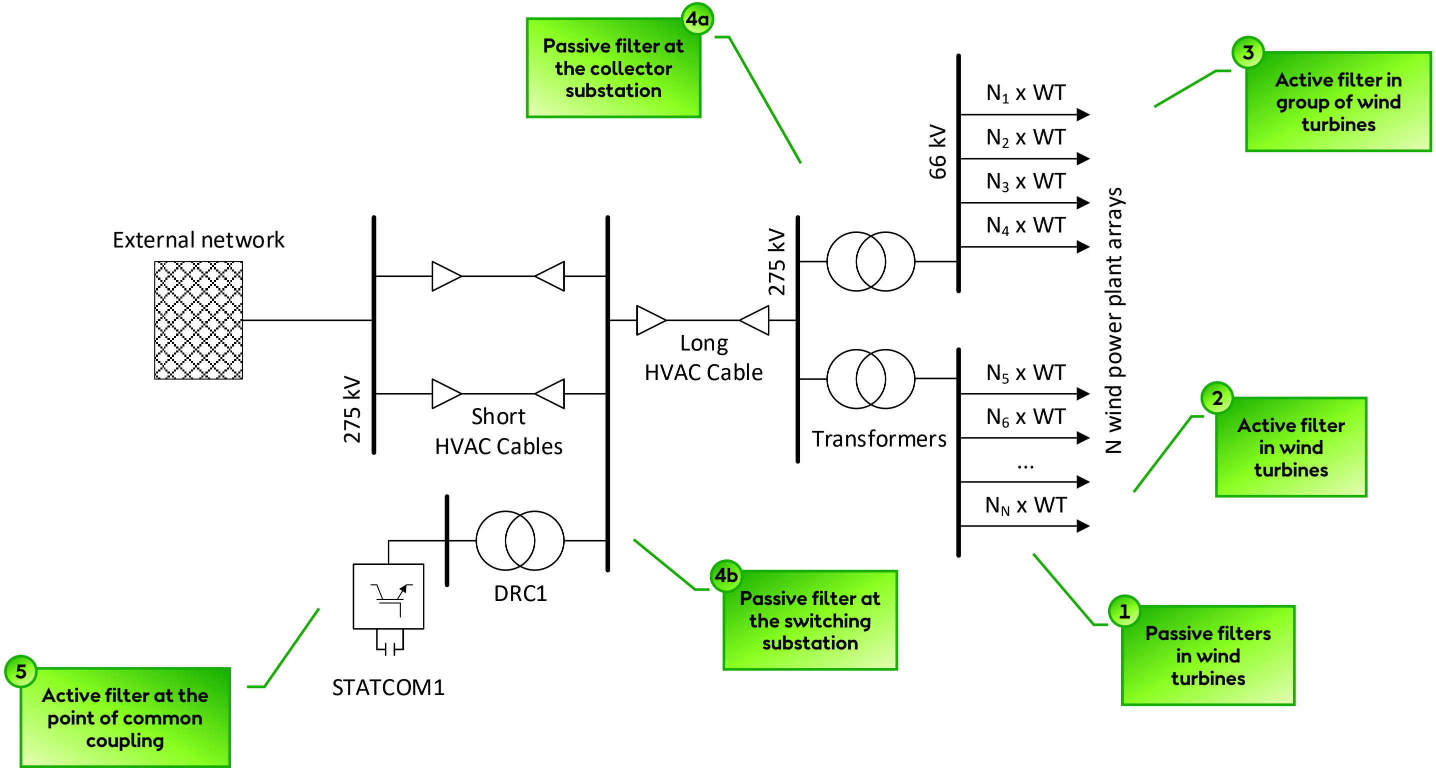
Harmonic generation from wind turbines

Harmonics from the external network

Harmonic generation from other active sources

Harmonic mitigation methods in offshore wind power plants

Passive and active harmonics



Passive filter at the collector substation

Active filter in group of wind turbines

Active filter in wind turbines

Passive filter at the switching substation

Passive filters in wind turbines

Active filter at the point of common coupling

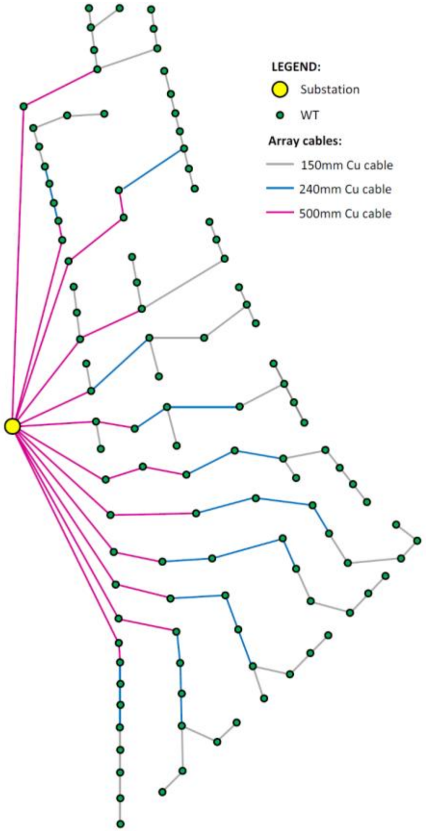
Source: Ł. H. Kocewiak, S. K. Chaudhary, and B. Hesselbæk, “Harmonic Mitigation Methods in Large Offshore Wind Power Plants,” in Proc. *The 12th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms*, 22-24 October 2013, p. 443-448.

Active Filtering in Wind Turbines

Impedance shaping and resonance damping

Electrical infrastructure

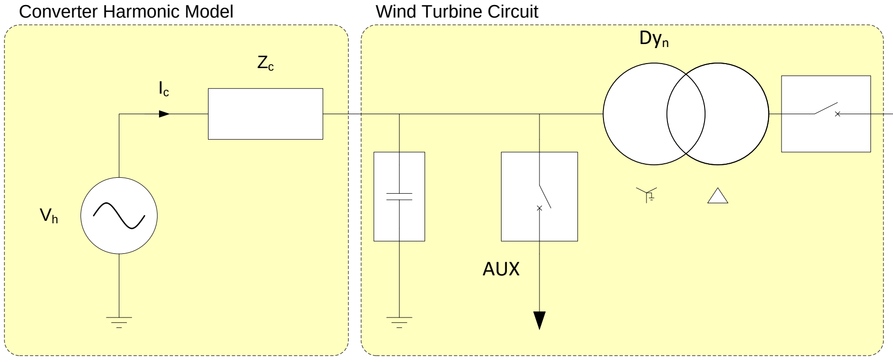
- 82.5km of export cable
- 152km of array cables with three different cross sections
- 111 WTs of rated capacity 3.6MW
- Three groups of WTs contain 37 WTs connected to one offshore main transformer via four arrays
- The WTs are equipped with full-load converter

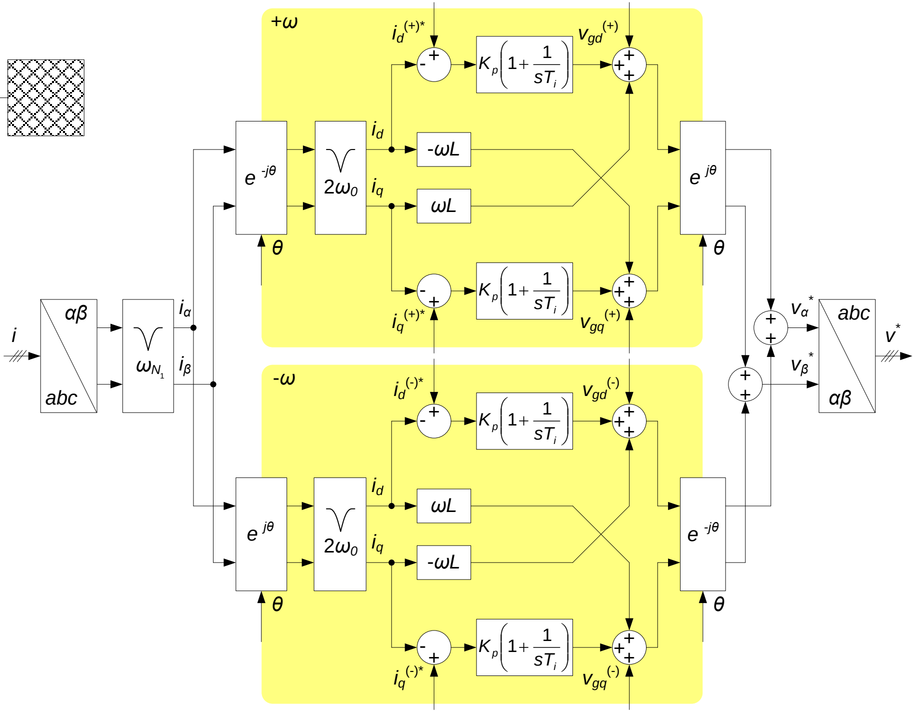


Ørsted

Active Filtering in Wind Turbines

Wind turbine modelling and tuning



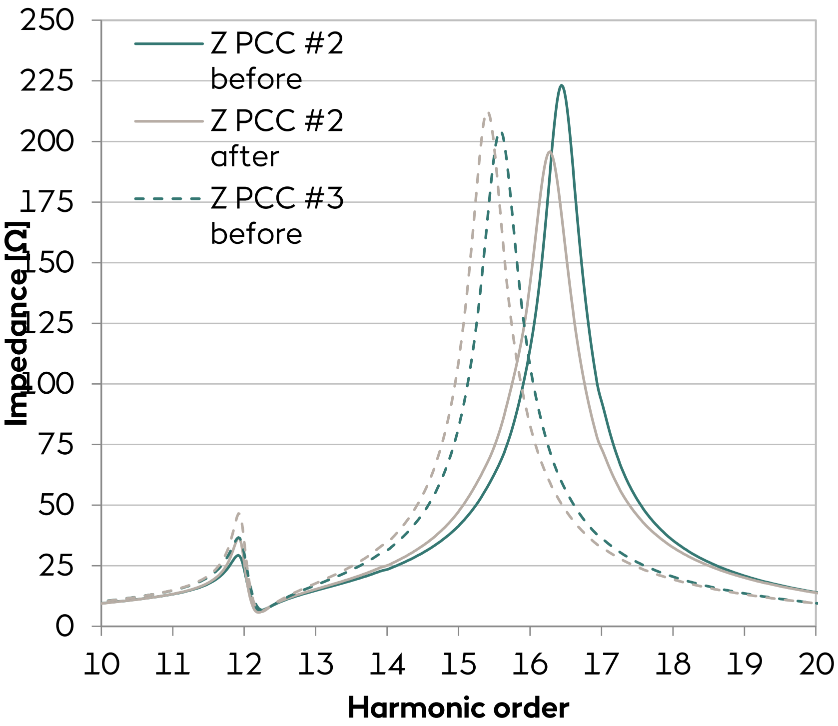


- Grid-side converter control strategy can affect the wind turbine harmonic emission and resonances in the system.
- Extra harmonic active filtering can be introduced by additional controller attenuation.
- Notch filters are of common practise to improve wind turbine controller noise rejection capability.

Source: Ł. H. Kocewiak, B. Laudal Øhlenschlæger Kramer, O. Holmstrøm, K. Høj Jensen, L. Shuai, *"Resonance Damping in Array Cable Systems by Wind Turbine Active Filtering in Large Offshore Wind Power Plants,"* IET Renewable Power Generation, Institution of Engineering and Technology, 6 July 2017, Volume 11, Issue 7, Page(s) 1069-1077.

Active Filtering in Wind Turbines

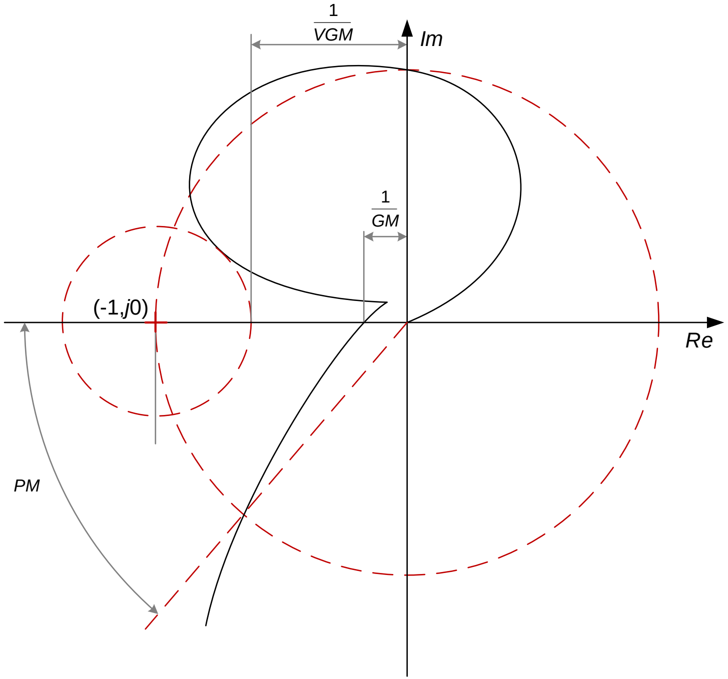
Resonance shift and distortion profile

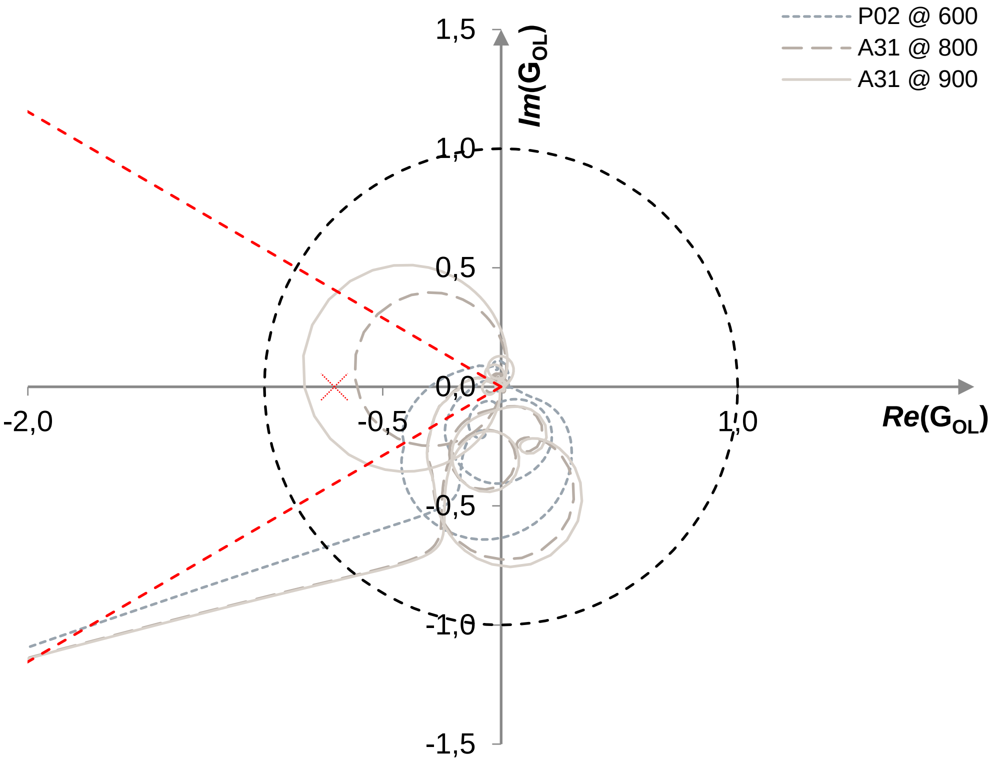


Source: C. F. Jensen, Ł. H. Kocewiak, Z. Emin, "*Amplification of Harmonic Background Distortion in Wind Power Plants with Long High Voltage Connections*," CIGRÉ Biennial Session, CIGRÉ, 21-26 August 2016, Paris, France, C4-112.

Active Filtering in Wind Turbines

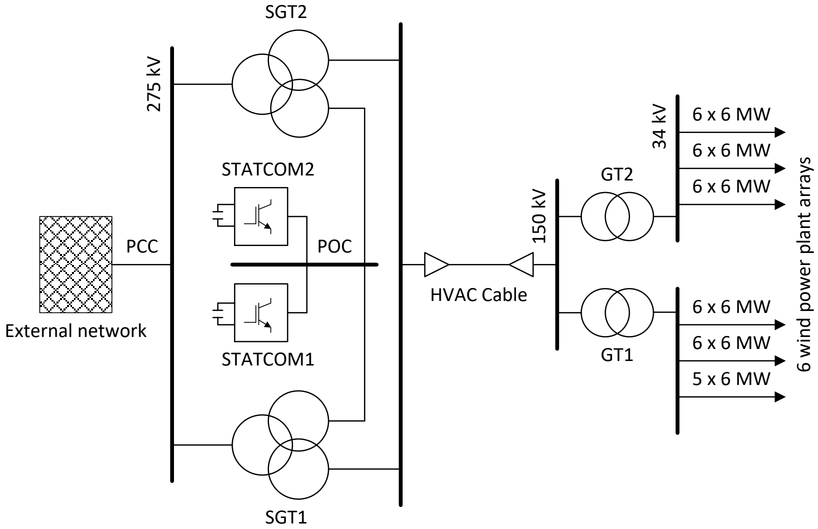
Resonance shift and distortion profile

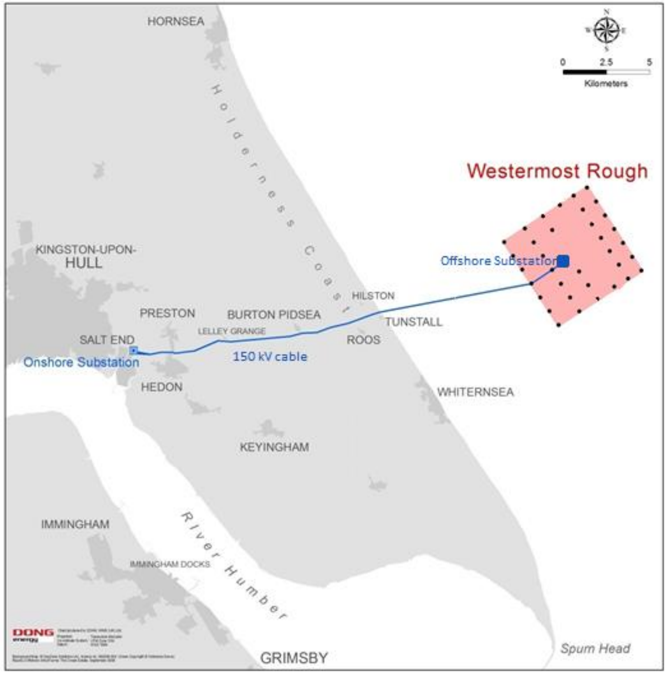




Active Filtering in STATCOMs

Harmonic compensation at the remote node





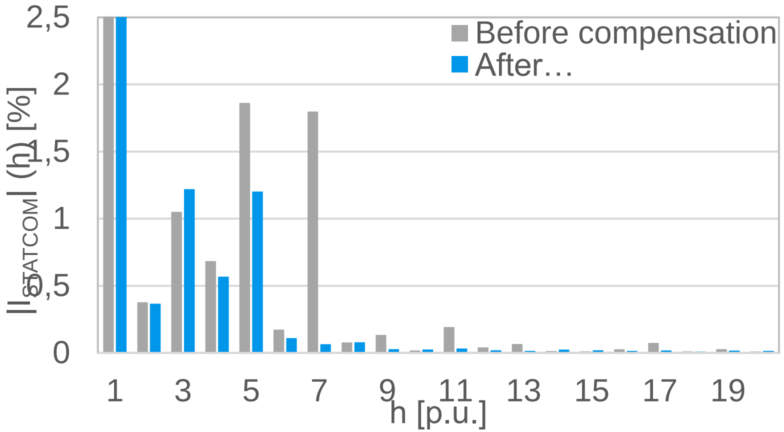
Electrical infrastructure

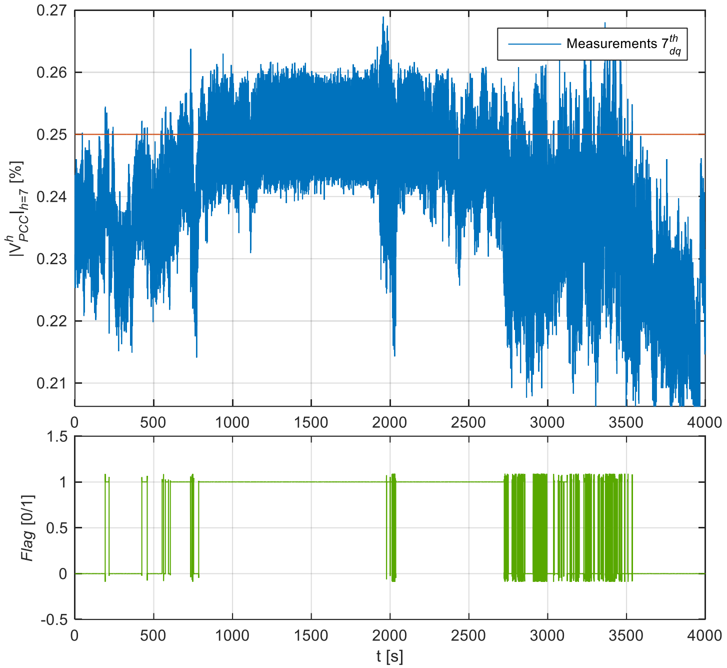
- WMR WPP two identical 25 MVar PCS 6000 STATCOM from ABB installed at Onshore Substation (OSS).
- WPP consists of 35 WTs with rated power of 6 MW, totaling 210 MW installed total capacity.
- Active Filtering (AF) of the voltage HD at the 275 kV PCC busbar.

Source: Ł. H. Kocewiak, M. Gautschi, L. Zeni, B. Hesselbæk, N. Barberis Negra, T. Stybe Sørensen, B. Blaumeiser, S. Vogelsanger, "*Power Quality Improvement of Wind Power Plants by Active Filters Embedded in STATCOMs*," in Proc. The 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 15-17 November 2016, Vienna, Austria.

Active Filtering in STATCOMs

Harmonic compensation at the remote node





Harmonic measurements

- One of the two STATCOMs was upgraded with AF functionality to reduce the harmonic voltage HD levels of the 7th harmonic.
- Local harmonic current compensation can effectively be done by STATCOMs.
- AF controller show clearly the 7th voltage harmonic clamping to the defined reference level of 0.25%.

International standards and their application

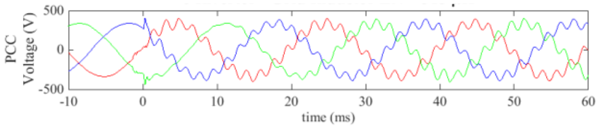
- **IEC 61000-4-7**
  - Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto
- **IEC 61000-4-30**
  - Testing and measurement techniques – Power quality measurement methods
- **IEC 61400-21-1**
  - Measurement and assessment of electrical characteristics – Part 1 – Wind Turbines
- **IEC 61400-21-3**
  - Wind turbine harmonic model and its application
- **IEC 61000-3-6**
  - Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems
- **IEEE Std 519**
  - IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Area #2
Stability

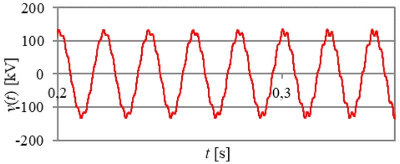
Background and Motivation

Real-life instability challenges

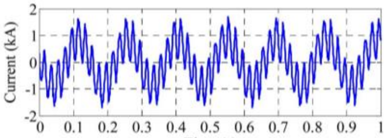
Oscillations in PV systems with harmonic resonances[1]



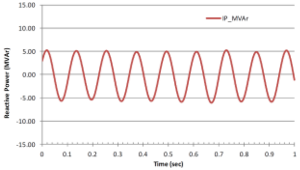
Oscillations in wind PP with HVDC and harmonic resonances[2]



Oscillations in systems with Type 3 WTs and series compensation[3]



Oscillations in Type 4 WTs in transmission grids[4]



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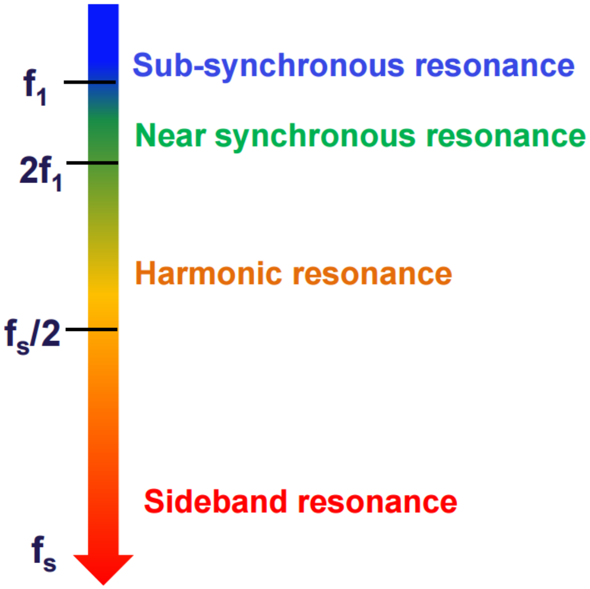
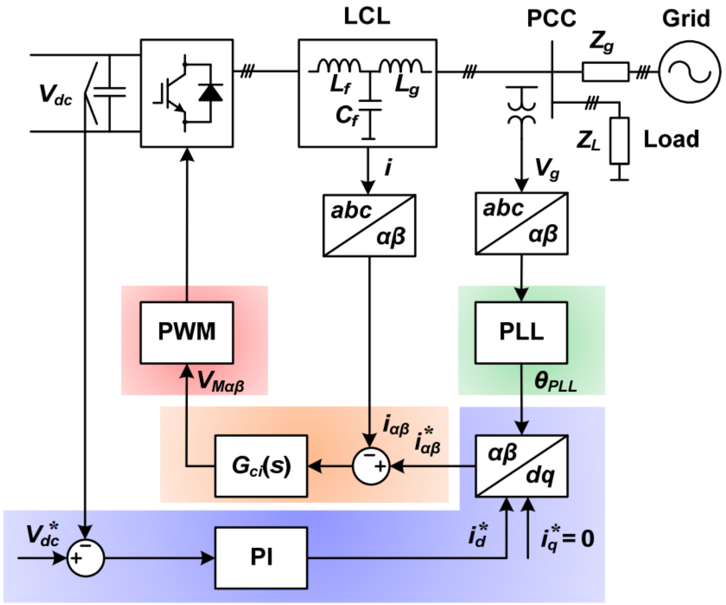
[1] F. Ackermann et al., “Stability prediction and stability enhancement for large-scale PV Power plants,” in Proc. 7th International Symposium on Power Electronics for Distributed Generation Systems, 2016.
[2] C. Buchhagen et al, “Harmonic Stability – Practical Experience of a TSO,” in Proc. The 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, 2016.
[3] L. Wang et al., “Investigation of SSR in Practical DFIG-Based Wind Farms Connected to a Series-Compensated Power System,” IEEE Transactions on Power Systems, 2015.
[4] L. Shuai et al, “Eigenvalue-based Stability Analysis of Sub-synchronous Oscillation in an Offshore Wind Power Plant,” in Proc. The 17th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, 2018.

Multi-timescale Stability Investigation



f_1: Grid fundamental frequency; f_s: Switching frequency



Control diagram of grid-connected VSCs

Source: X. Wang, “Modeling and Control of Voltage Source Converters and AC Drives,” Industrial/PhD Course, ET-AAU, 03/2016.

Recommendations

Stability analysis workflow

- **Investigate small-signal stability**

Use frequency domain methods to show the system stability. Investigate the root cause in case of instability.

- **Validate small-signal stability**

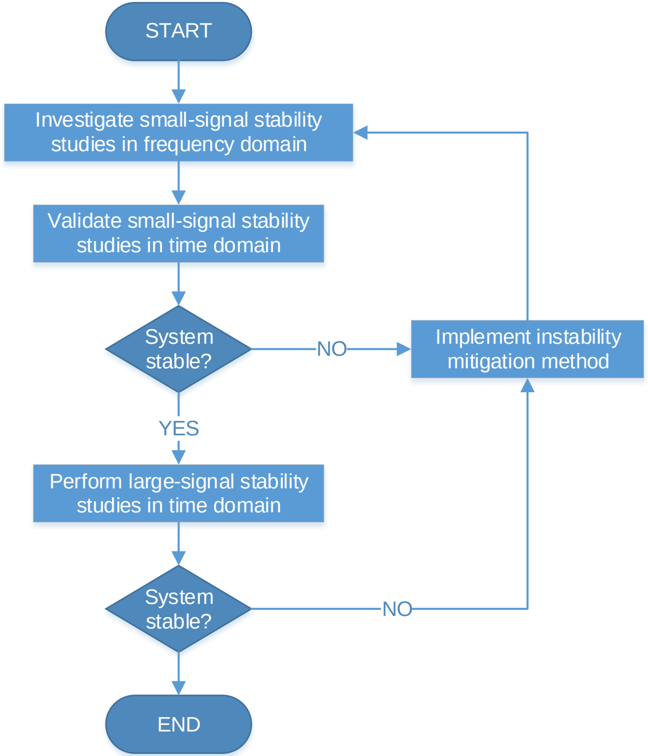
Reproduce the frequency domain results in time domain for specific operating points using non-linear models.

- **Perform large-signal stability**

Perform time domain simulations including large-signal perturbations such as faults, phase jumps, etc.

- **Implement instability mitigation**

Apply specific mitigation methods depending on the root cause as well asset lifecycle phase.



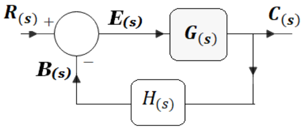
Ł. Kocewiak, R. Blasco-Giménez, C. Buchhagen, J. B. Kwon, Y. Sun, A. Schwanka Trevisan, M. Larsson, X. Wang, "Overview, Status and Outline of Stability Analysis in Converter-based Power Systems," in Proc. The 19th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 11-12 November 2020.

Stability Analysis Methods

Stability analysis methods

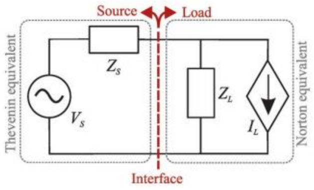
Transfer-function-based

- Classical approach used in control theory.
- Indicates stability and quantifies robustness.
- Inconvenient for root cause analysis.



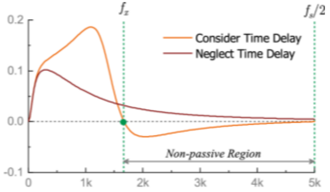
Impedance-based

- Previously used in DC grids.
- Indicates stability but difficult to quantify robustness.
- Difficult to perform root cause analysis.



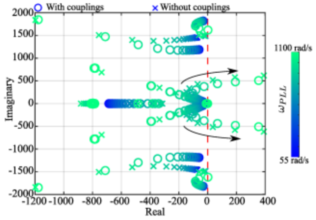
Passivity-based

- Commonly used in traction / railway systems.
- Indicates stability but difficult to quantify robustness.
- Difficult to perform root cause analysis.



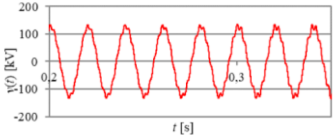
Eigenvalue-based

- Commonly used in power system studies.
- Indicates stability and quantifies robustness.
- Convenient to perform root cause analysis.



Time domain

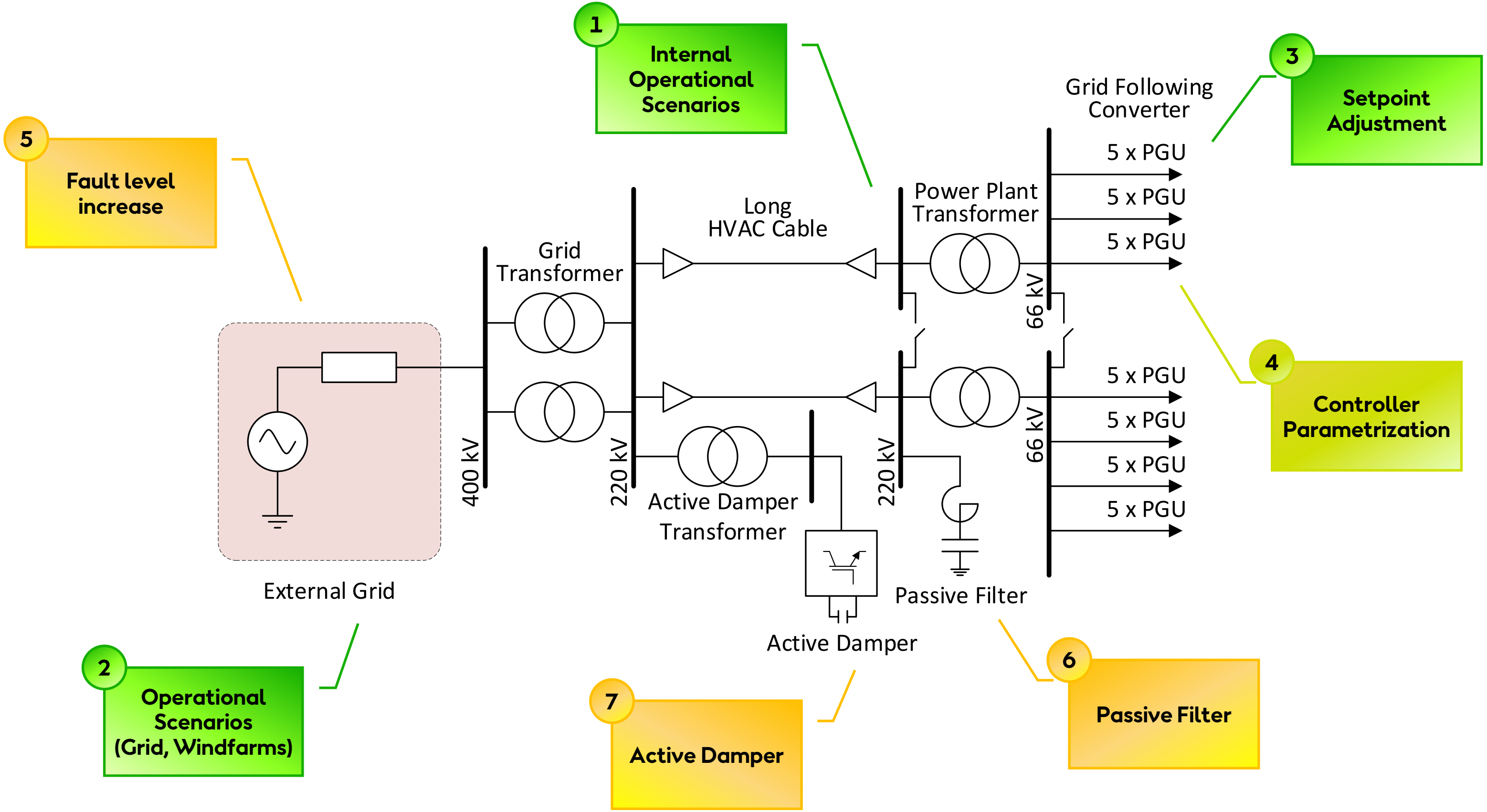
- EMT commonly used for dynamic simulations.
- Indicates stability but difficult to quantify robustness.
- Convenient to confirm stability.



CIGRE C4.49, “Multi-frequency stability of converter-based modern power systems”.

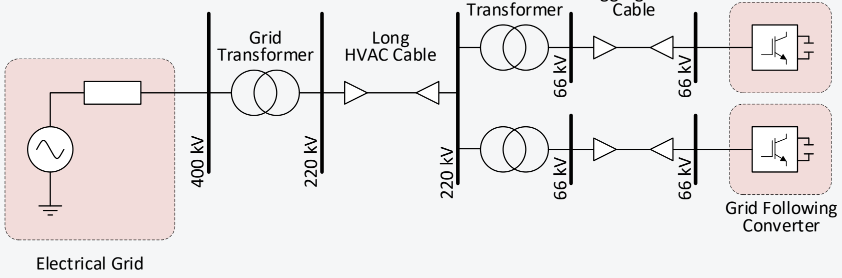
Stability in Renewable-based Power Systems

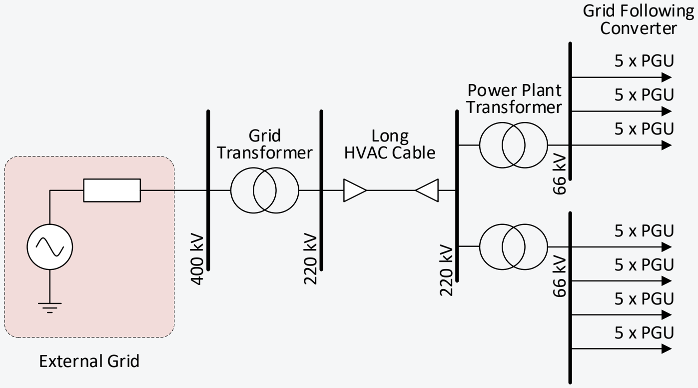
Instability mitigation methods (preventive and corrective)



Benchmark System

Detailed and aggregated





- **Cable**

3x150mm^2, 3x500mm^2, 1200mm^2

- **Transformer**

P_n = 430 MVA, 270/200 MVA, 12 MVA

- **Grid**

S_n = 3000 MVA, 600 MVA

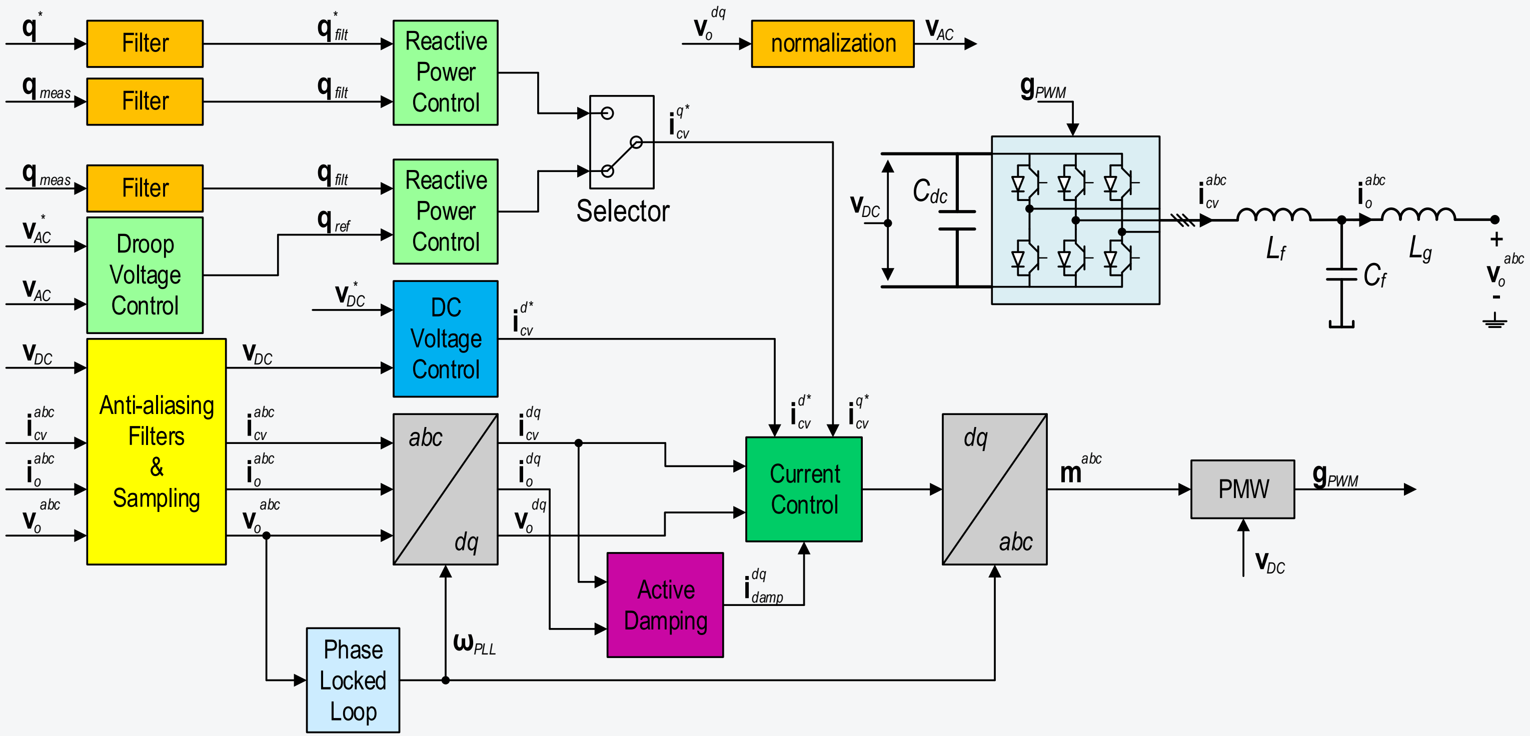
- **Power generation unit**

S_b = 12 MW, f_s = 2950 Hz

Source: Ł. Kocewiak, Ch. Buchhagen, Y. Sun, X. Wang, G. Lietz, M. Larsson, "Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems," in Proc. The 19th International Workshop on Large-Scale Integration of
Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 11-12 November 2020.

Power Generation Unit

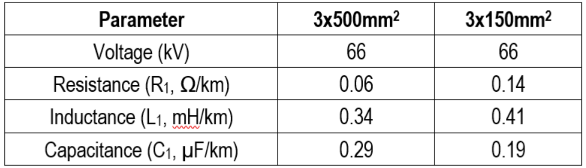
Grid following converter



Source: Ł. Kocewiak, Ch. Buchhagen, Y. Sun, X. Wang, G. Lietz, M. Larsson, “Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems,” in Proc. The 19th International Workshop on Large-Scale Integration of as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 11-12 November 2020.

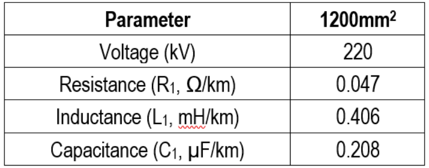
System Parameters

Table 1 Collection cable equivalent electrical parameters.



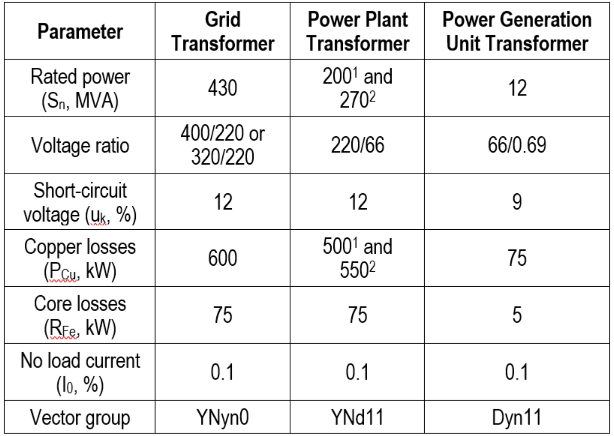
Parameter	3x500mm^2	3x150mm^2
Voltage (kV)	66	66
Resistance (R_1, Ω/km)	0.06	0.14
Inductance (L_1, mH/km)	0.34	0.41
Capacitance (C_1, μF/km)	0.29	0.19

Table 2 Transmission cable equivalent electrical parameters.



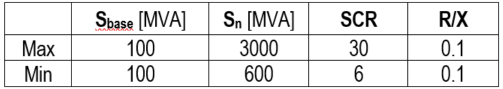
Parameter	1200mm^2
Voltage (kV)	220
Resistance (R_1, Ω/km)	0.047
Inductance (L_1, mH/km)	0.406
Capacitance (C_1, μF/km)	0.208

Table 3 Transformers electrical parameters.



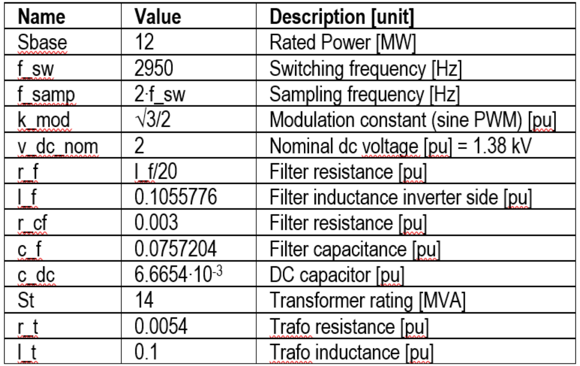
Parameter	Grid Transformer	Power Plant Transformer	Power Generation Unit Transformer
Rated power (S_n, MVA)	430	200^1 and 270^2	12
Voltage ratio	400/220 or 320/220	220/66	66/0.69
Short-circuit voltage (u_k, %)	12	12	9
Copper losses (P_{Cu}, kW)	600	500^1 and 550^2	75
Core losses (R_{Fe}, kW)	75	75	5
No load current (I_0, %)	0.1	0.1	0.1
Vector group	YNyn0	YNd11	Dyn11

Table 4 Short-circuit power of the 400-kV grid.



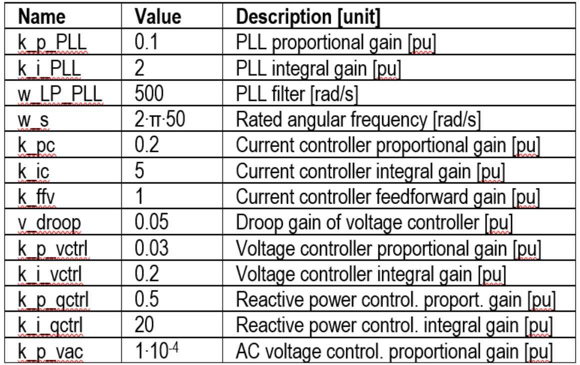
	S_{base} [MVA]	S_n [MVA]	SCR	R/X
Max	100	3000	30	0.1
Min	100	600	6	0.1

Table 5. List of basic parameters for assumed converter system.



Name	Value	Description [unit]
Sbase	12	Rated Power [MW]
f_sw	2950	Switching frequency [Hz]
f_samp	2·f_sw	Sampling frequency [Hz]
k_mod	√3/2	Modulation constant (sine PWM) [pu]
v_dc_nom	2	Nominal dc voltage [pu] = 1.38 kV
r_f	l_f/20	Filter resistance [pu]
l_f	0.1055776	Filter inductance inverter side [pu]
r_cf	0.003	Filter resistance [pu]
c_f	0.0757204	Filter capacitance [pu]
c_dc	$6.6654 \cdot 10^{-3}$	DC capacitor [pu]
St	14	Transformer rating [MVA]
r_t	0.0054	Trafo resistance [pu]
l_t	0.1	Trafo inductance [pu]

Table 6. List of controller parameters used in converter system.

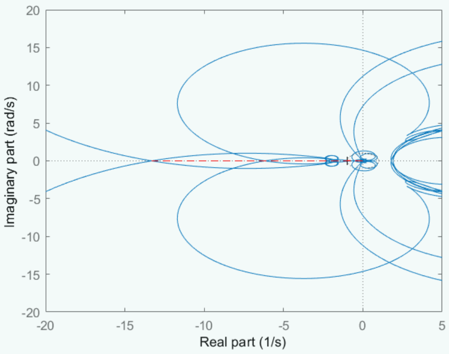


Name	Value	Description [unit]
k_p_PLL	0.1	PLL proportional gain [pu]
k_i_PLL	2	PLL integral gain [pu]
w_LP_PLL	500	PLL filter [rad/s]
w_s	2·π·50	Rated angular frequency [rad/s]
k_pc	0.2	Current controller proportional gain [pu]
k_ic	5	Current controller integral gain [pu]
k_ffv	1	Current controller feedforward gain [pu]
v_droop	0.05	Droop gain of voltage controller [pu]
k_p_vctrl	0.03	Voltage controller proportional gain [pu]
k_i_vctrl	0.2	Voltage controller integral gain [pu]
k_p_qctrl	0.5	Reactive power control. proport. gain [pu]
k_i_qctrl	20	Reactive power control. integral gain [pu]
k_p_vac	$1 \cdot 10^{-4}$	AC voltage control. proportional gain [pu]

Source: Ł. Kocewiak, Ch. Buchhagen, Y. Sun, X. Wang, G. Lietz, M. Larsson, “Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems,” in Proc. The 19th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 11-12 November 2020.

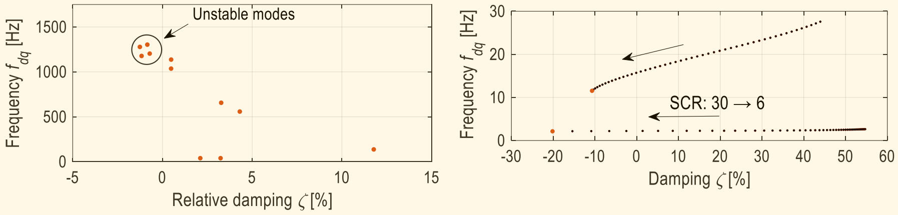
Small-signal Stability Investigation

Impedance-based



- Impedance ratio between aggregated PGU and the grid.
- Relevant for SISO or MIMO (e.g. in dq) systems.
- Generalized Nyquist stability criterion is applied: unstable.
- Phase and gain margins are calculated:
  -22 dB at 915 Hz and -3.0° at 1190 Hz.

Eigenvalue-based

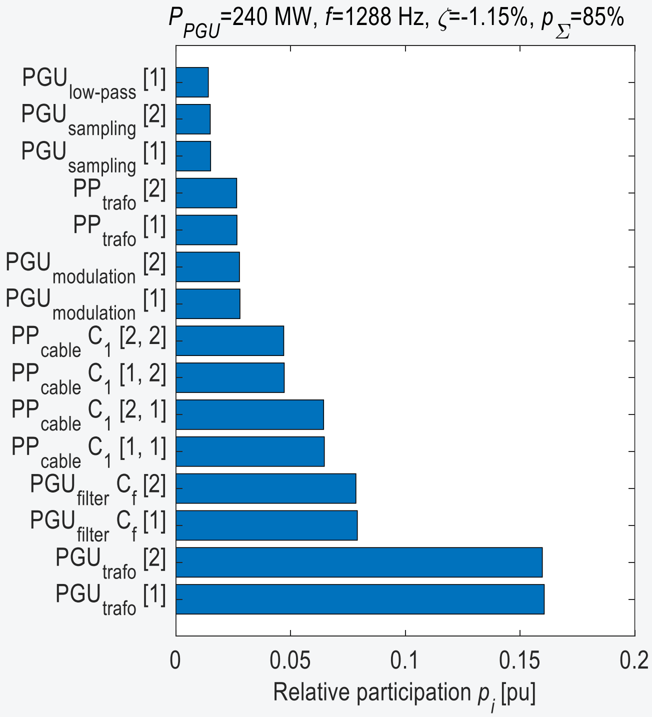


- Frequencies of critical eigenvalues:
  1190 Hz, 1215 Hz, 1288 Hz, 1317 Hz.
- Participation factor analysis is used.
- Damping ratio is estimated to evaluate the robustness:
  -0.6%, -0.74%, -1.05%, -1.15%.
- Sensitivity analysis: grid short-circuit ratio: from 30 to 6.

Source: Ł. Kocewiak, Ch. Buchhagen, Y. Sun, X. Wang, G. Lietz, M. Larsson, “Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems,” in Proc. The 19th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH.

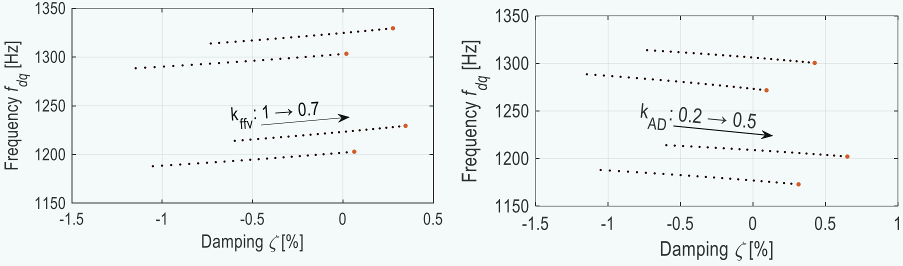
Participation Factor Analysis

- **Power plant**
  - Power plant transformer
  - Medium voltage cable
- **Converter**
  - Anti-aliasing low-pass filter
  - Modulation delay
  - Sampling delay
  - Power generation unit transformer
  - Power generation unit filter



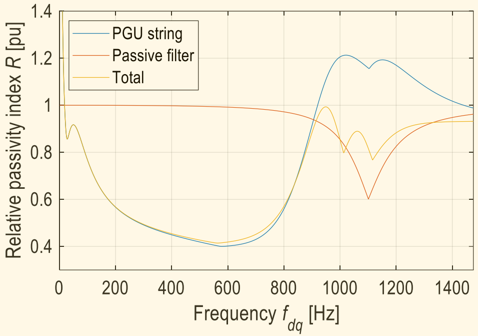
Instability Mitigation Methods

Controller Parametrization



- Controller parameters sensitivity analysis.
- Voltage feed-forward gain tuning: k_{ffv} from 1 to 0.7.
- Active damping gain tuning: k_{AD} from 0.2 to 0.5.

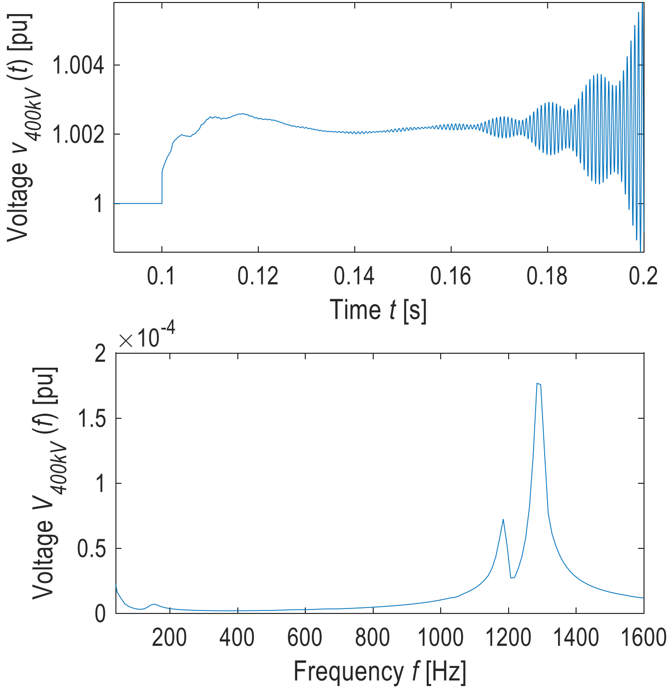
Passive Filter



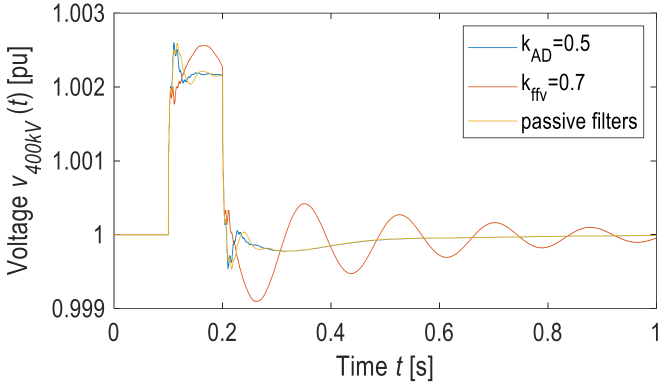
- Type: single-tuned
- Location: end of string
- Tuning frequency: 1100 Hz
- Size: 0.25 Mvar
- Q-factor: 6

Source: Ł. Kocewiak, Ch. Buchhagen, Y. Sun, X. Wang, G. Lietz, M. Larsson, "Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems," in Proc. The 19th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 11-12 November 2020.

Time-domain simulations



Time domain simulation results showing 400-kV busbar voltage waveform of the unstable base case.



Step response to evaluate the effectiveness of various mitigation methods.

- **Parameters**
  - Voltage feed-forward gain 0.7
  - Active damping loop gain 0.5
  - Single-tune filter at 1100 Hz

Relevant Working Groups on Stability

- **CIGRE C4.49** "Multi-frequency stability of converter-based modern power systems"
- **CIGRE C4/B4.52** "Guidelines for Sub-synchronous Oscillation Studies in Power Electronics Dominated Power Systems"
- **IEC SC8a TR** "Control interaction and power system damping (due to grid resonances)"
- **CIGRE B4.81** "Interaction between nearby VSC-HVDC converters, FACTs devices, HV power electronic devices and conventional AC equipment"
- **IEC TR 61000-2-15** "Assessment of instability/non-linear phenomena between AC-DC/DC-DC Converters and the Grid"
- **CIGRE B4.67** "AC side harmonics and appropriate harmonic limits for VSC HVDC"
- **CIGRE B4.70** "Guide for Electromagnetic Transient Studies involving VSC converters"
- **CIGRE C2/C4.41** "Impact of high penetration of inverter-based generation on system inertia of networks"
- **IEEE P2800** "Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems", "Wind and Solar Plant Interconnection Performance Working Group"

Summary

What next?

- **Which method is the best to be used by the industry to** analyze converter-based power systems?
- **Are there any challenges for the industry and academia to** provide suitable and accurate models?
- **Is it possible to** specify generic rules regarding the grid converter coordination / interoperability?
- **Do the industry and academia need an** international standard regarding converter operation in power systems?

Q&A