ELEC-E8424 DISTRIBUTED GENERATION TECHNOLOGIES, 7.11.2023

Power Electronic Converters in Power Systems

Dr. Mikko Routimo, Control Architect, Senior Principal Engineer, ABB System Drives

Power electronic converters in power systems

Content

- Converters for distributed generation
- What kind of functionality is needed in order to connect distributed generation to power grid?
- Simulation studies

Power electronic converters in power systems

At the end of this session students will be able to answer the following questions

- Why do we need standards and grid codes?
- What is the most important content of the grid codes from the converter point of view?
- What are the main features required from the converter to connect distributed generation to the grid?

Why renewables?

- The use of electricity is growing at a rapid pace especially as emerging economies industrialize and register strong economic growth
- Today, renewables account for an increasing share of the energy mix and make, in some countries, and important contribution to meeting carbon reduction targets
- Wind and solar power generation can significantly contribute to the big challenge of meeting these growing needs while addressing environmental impact
- In 2022, the total electrical energy production in the world was 29 165 TWh*
  - Wind 2 129 TWh* + solar PV: 1 293 TWh* = 3422 TWh (11.7 %)

906 GW ≈ 566

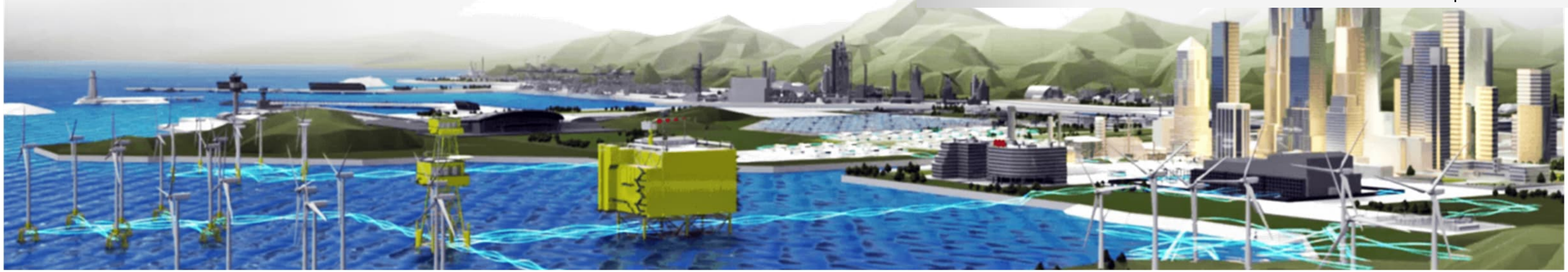
69 GWp installed in 2022**

The equivalent of OL3 nuclear plants

1177 GWp ≈ 735

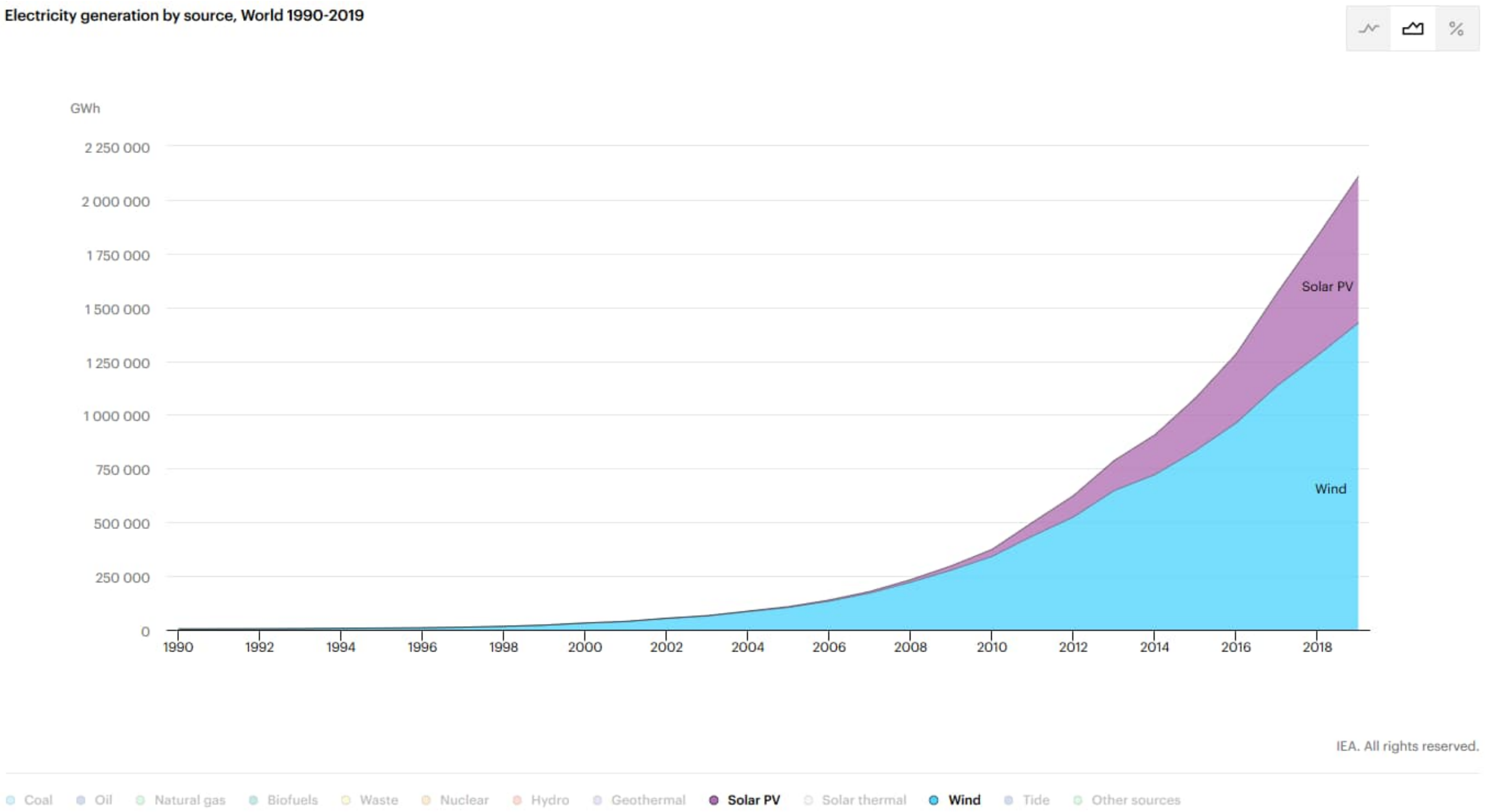
237 GWp installed in 2022***

The equivalent of OL3 nuclear plants



* IEA, Accessed: November 6, 2023. https://www.iea.org/statistics/
** Cumulative installed wind power capacity worldwide from 2001 to 2022 (in gigawatts). Statista. Statista Inc.. Accessed: November 6, 2023. https://www.statista.com/statistics/268363/installed-wind-power-capacity-worldwide/
*** Cumulative installed solar PV capacity worldwide from 2001 to 2022 (in gigawatts). Statista. Statista Inc.. Accessed: November 6, 2023. https://www.statista.com/statistics/268363/installed-wind-power-capacity-worldwide/

Electricity generation by source, Wind and Solar PV



Source: IEA https://www.iea.org/statistics/

Why renewables?

2019

- The use of electricity is growing at a rapid pace especially as emerging economies industrialize and register strong economic growth
- Today, renewables account for an increasing share of the energy mix and make, in some countries, and important contribution to meeting carbon reduction targets
- Wind and solar power generation can significantly contribute to the big challenge of meeting these growing needs while addressing environmental impact
- In 2019, the total electrical energy production in the world was 27 044 TWh*
  - Wind + solar PV = 2 108 TWh*
  - Coal: 9 914 TWh* (36.0 %), natural gas 6 346 TWh* (23.4 %), hydro 4 329 TWh* (16.0 %), nuclear 2790 TWh* (10.3 %)

743 GW ≈ 464

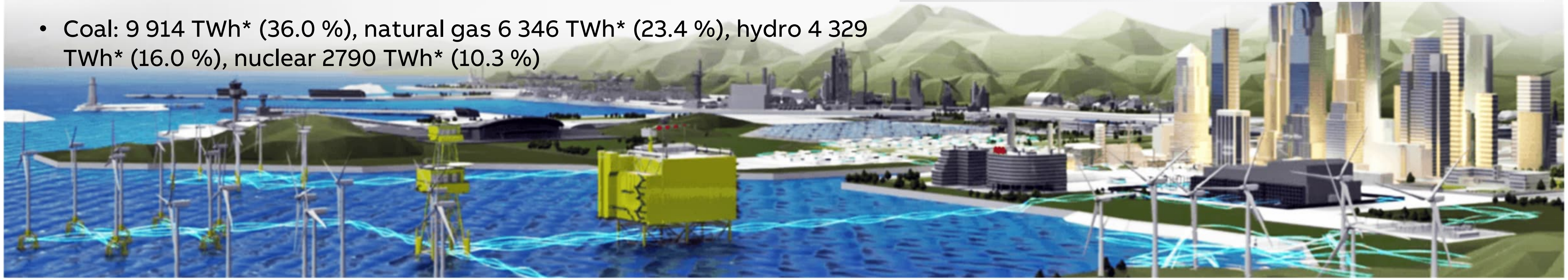
91,9 GW installed in 2020**

The equivalent of OL3 nuclear plants

634 GWp ≈ 396

116,9 GW installed in 2019***

The equivalent of OL3 nuclear plants

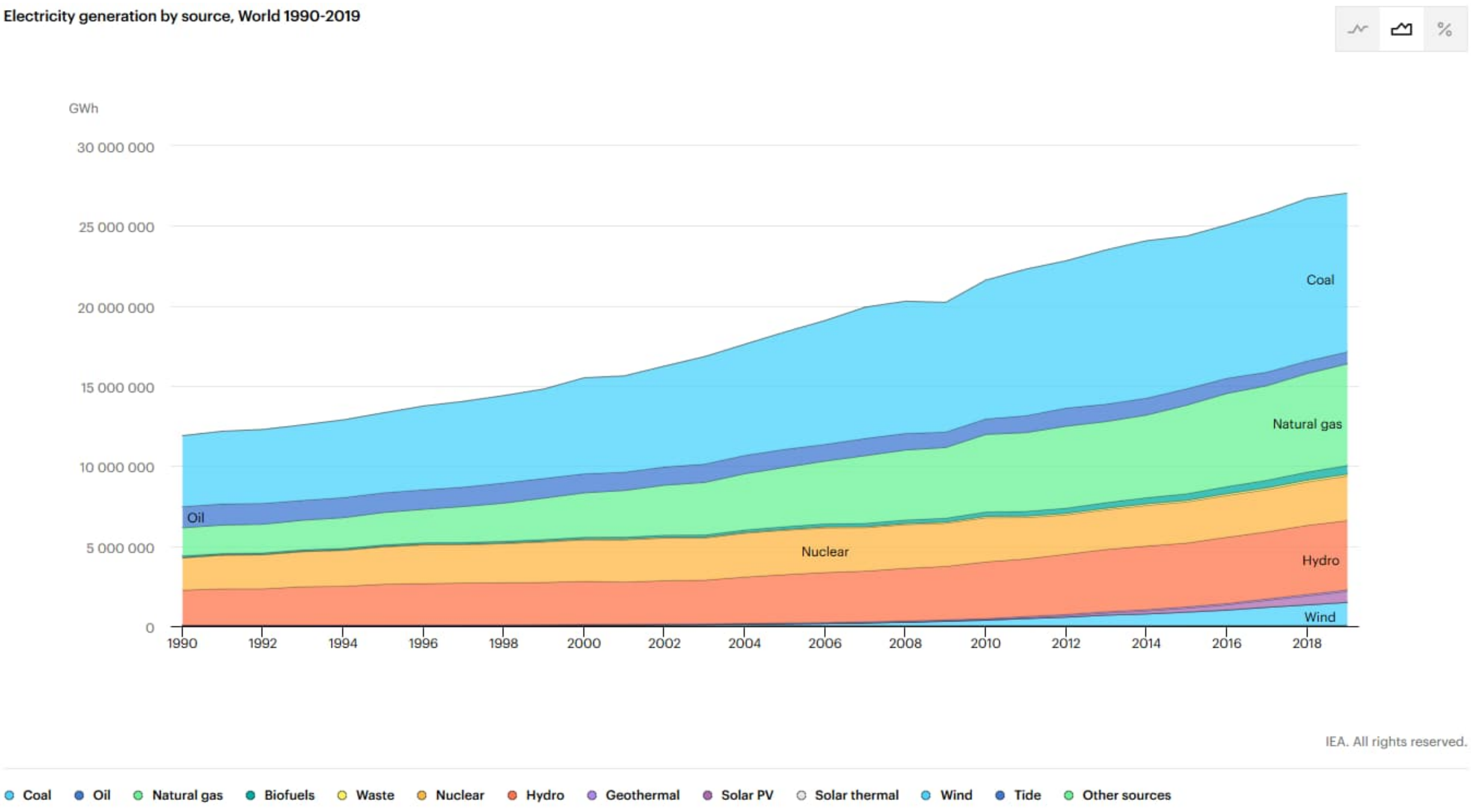


* IEA, Accessed: November 6, 2021. https://www.iea.org/statistics/

** GWEC. (2021). Global cumulative installed wind power capacity from 2001 to 2020 (in megawatts). Statista. Statista Inc.. Accessed: November 6, 2021. https://www.statista.com/statistics/268363/installed-wind-power-capacity-worldwide/

*** SolarPower Europe. (2020). Global new installed solar PV capacity from 2000 to 2019 (in megawatts). Statista. Statista Inc.. Accessed: November 6, 2021. https://www.statista.com/statistics/280220/global-new-installed-solar-pv-capacity/

Electricity generation by source



Source: IEA https://www.iea.org/statistics/

Control of distributed generation

[Edris Pouresmaeil: Control and Operation of Grid-Connected DC/AC Converters]

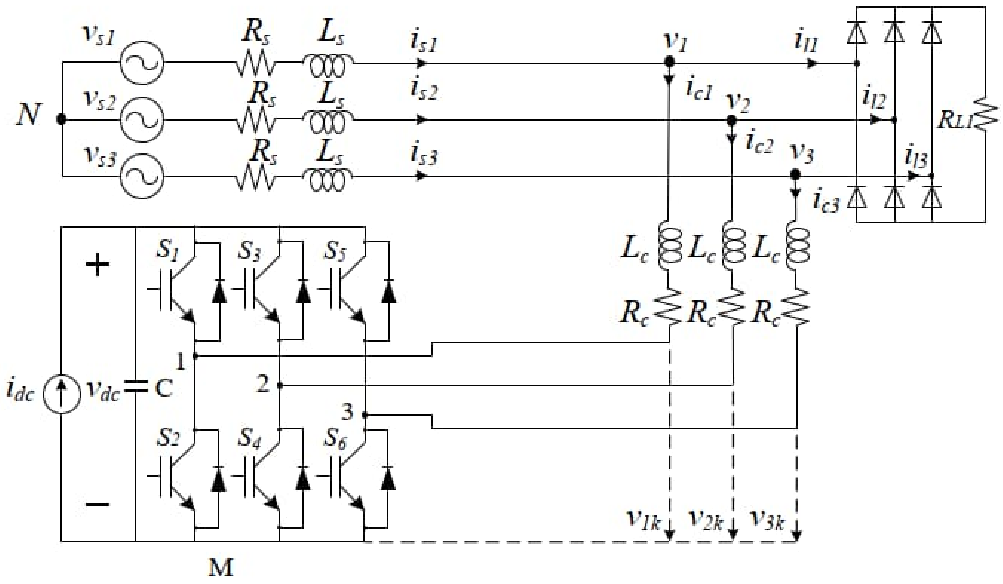


Fig. 4.1. General model of a grid-connected converter.

ABB Products for wind turbines

Wind turbine converters

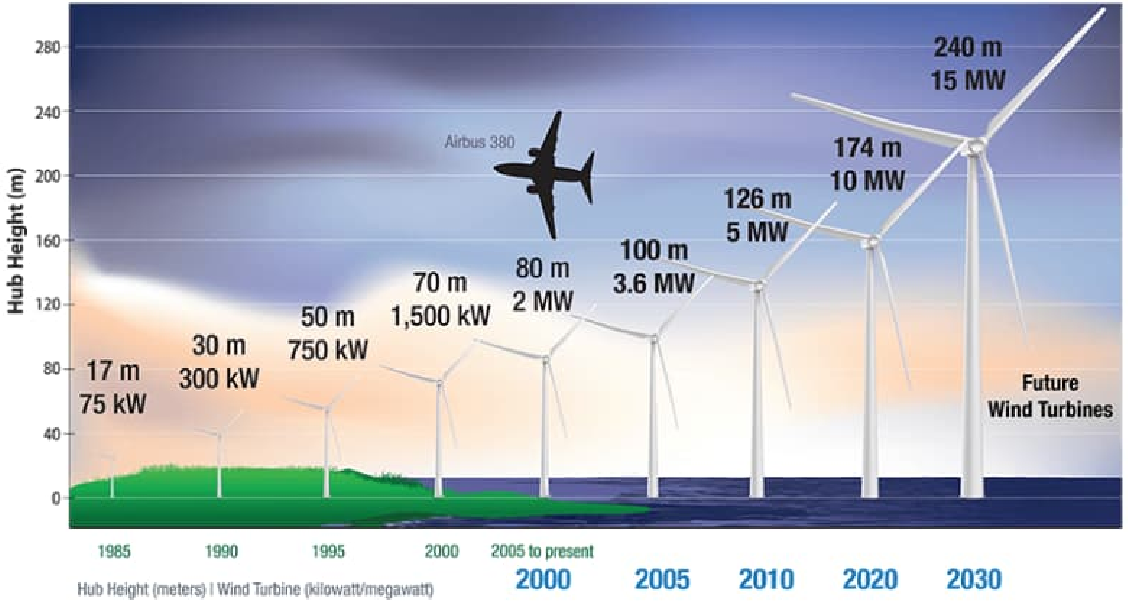
ACS880 - Low Voltage Converter

- Onshore or offshore turbines
- IGBT power modules
- Air and liquid-cooled
- Fault-ride-through
- Reactive power
- Support for different grid codes
- Full power converter
  - 0.8 to 8 MW
- Suitable for tower and nacelle installations

PCS6000 - Medium Voltage Converter

- Onshore or offshore turbines
- 4 to 15 MW
- 3.3 kV
- 3-level topology
- IGCT power modules
- Water-cooled
- Support for different grid codes
- Harmonic elimination control algorithm
- Suitable for tower base and nacelle installation

Wind turbine technology evolution



Prototypes of 14 MW offshore wind turbines already operating

Source: National Renewable Energy Laboratory (USA) – April 2020 Newsletter
The Leading Edge: April 2020 Wind Energy Newsletter | Wind Research | NREL

Wind turbine nacelle

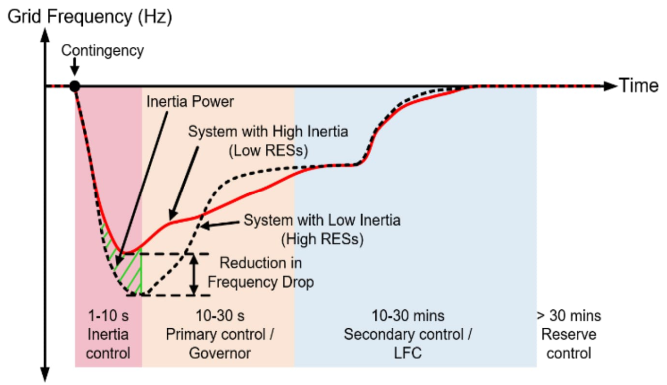
Grid Codes and Standards

Means to ensure compatibility and interoperability, and to guarantee stability and security of the grid

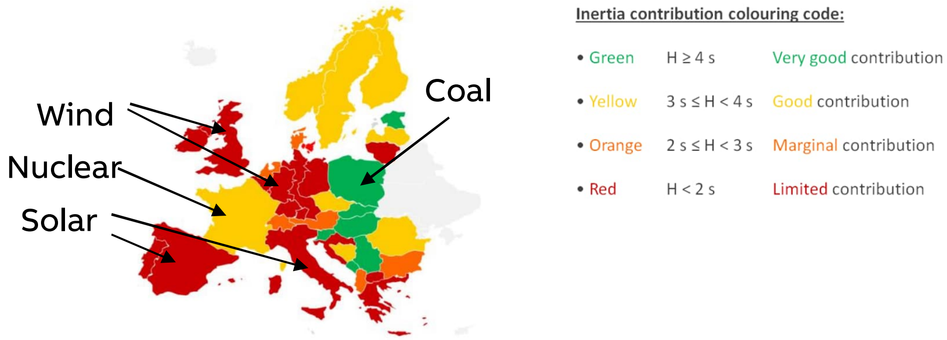
Renewables and distributed generation in power systems

Conventional electrical power generation vs. power electronics based generation

- Rotating machines / electronics
- Characteristics of the generators is different
- Operation principle is different
  - Maximum power point vs. production according demand
  - "Inertia in power system is reduced"
- Different fault current capacity
  - protection issues
- Unpredictable energy production in wind and solar
  - energy storages, demand response
- Sink for harmonics
- Sink for unbalance
- Creation and responsibility of the system voltage and frequency
  - "Grid following control" vs. "grid forming control"



Increase in frequency deviations (df/dt, Δf) due to reduced system inertia. Issues with protection methods (LFDD) because it reacts to slow → system instability



Future contribution to total system inertia (TYNDP 2030 scenario)*

* ENTSO-E Technical Report "High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters", 2018

Renewables and distributed generation in power systems

How to manage system consisting different types of power sources and generators?

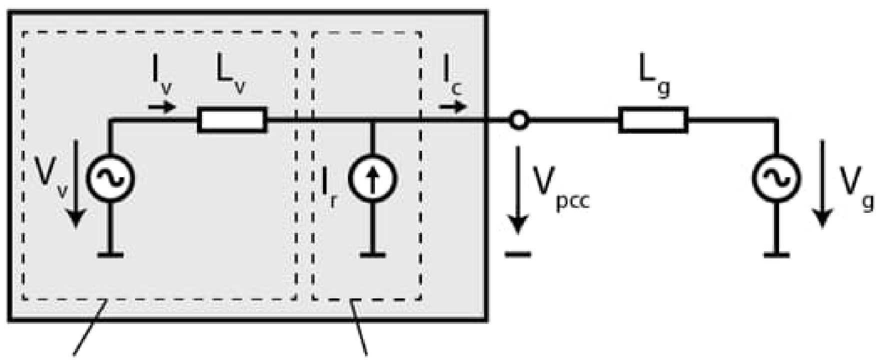
- Electrical characteristics of power electronic converter is completely different from the traditional (rotating) generators
  - Controlled current or voltage sources vs. synchronous machine with back emf
  - EMI and EMC
  - Operation during faults?
    - Fault current capacity
    - Disconnection?

→ **Coordination is required = grid codes and standards**

- **Define rules and guidelines to required actions needed to design and connect power plants to the grid**

The aim of the grid codes is to guarantee equal and non-discriminatory conditions for competition on the energy market, to ensure system security and to create harmonised connection terms for grid connections.

- The requirements are, in principle, similar both for distributed generation (i.e. power electronics based) and traditional power plants
- Distributed generation is required to participate maintaining the stability of the grid and to ”ride through” the faults

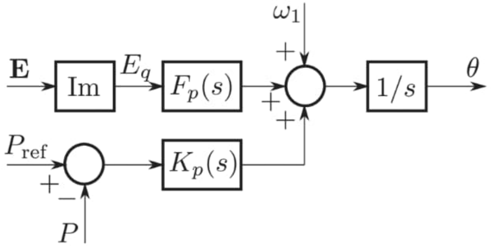


Voltage source behind impedance instead of standard stiff current control

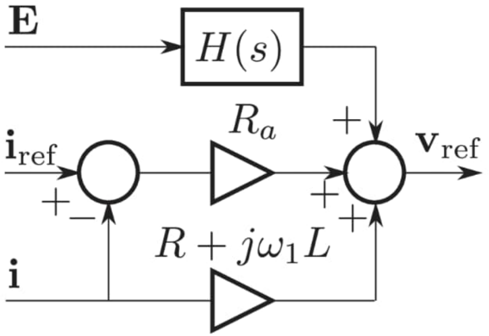
Control of distributed generation

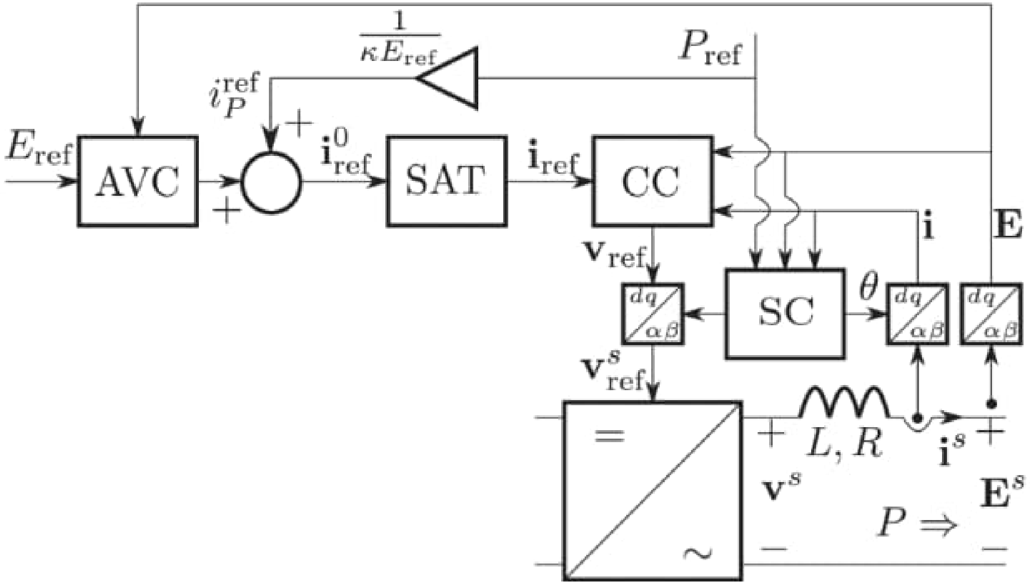
Control System

SC – Synchronization Controller

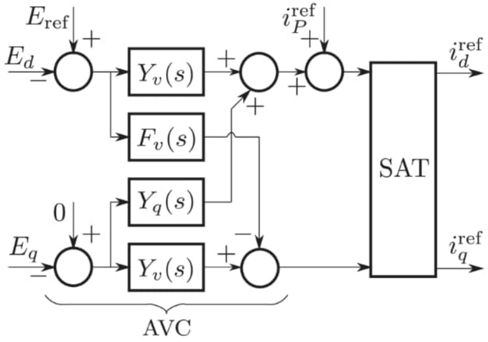


CC – Current Controller



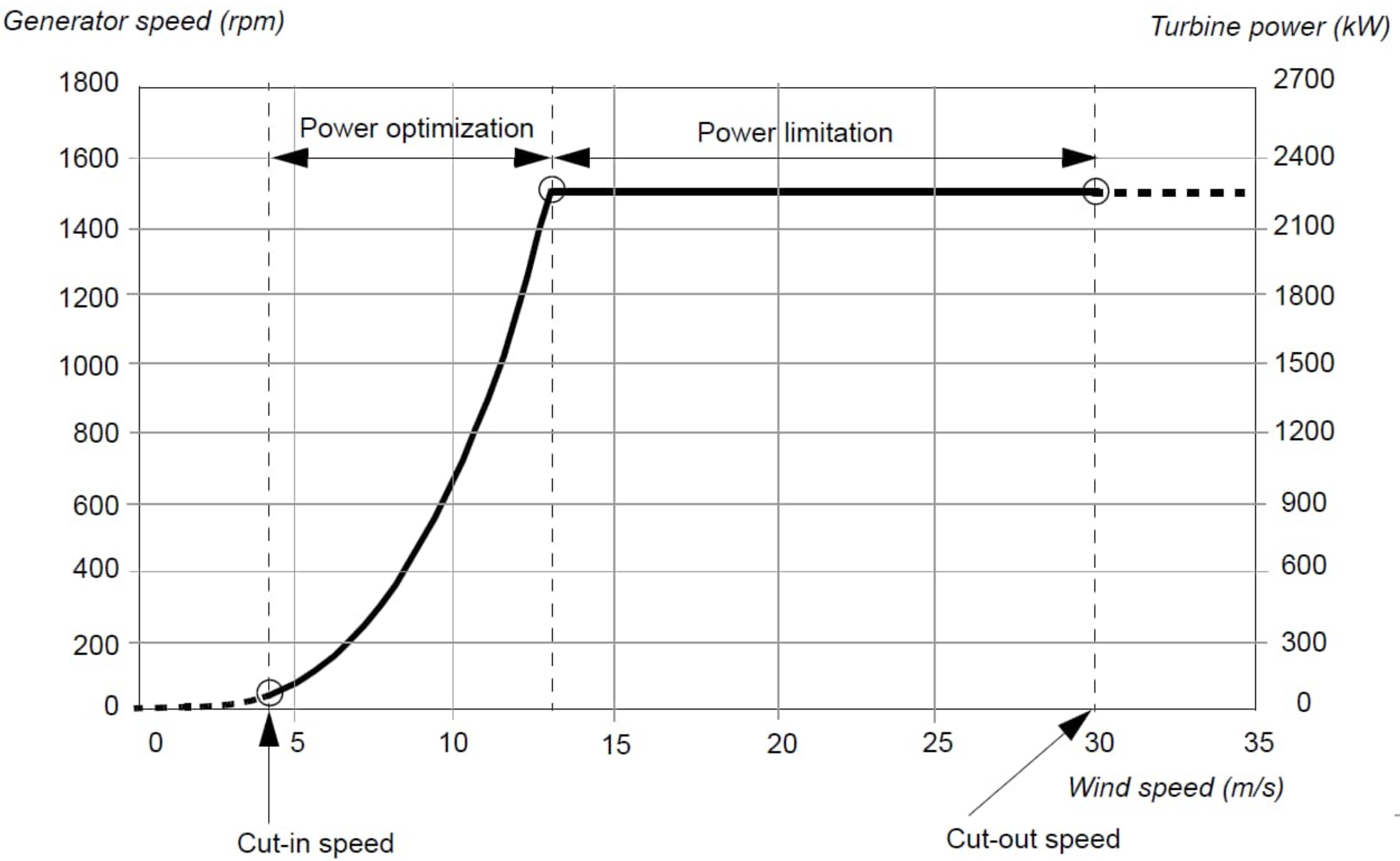


AVC – Ac-Voltage Controller

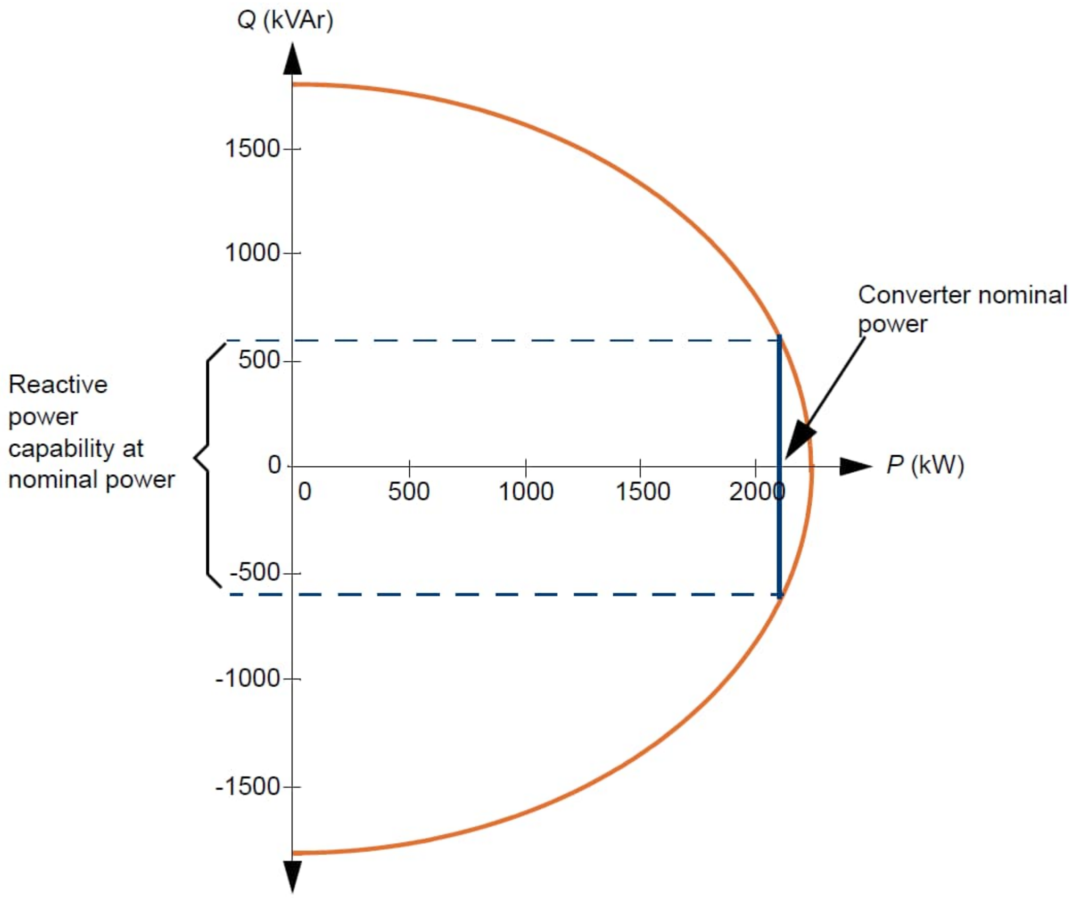


L. Harnefors, M. Schweizer, J. Kukkola, M. Routimo, M. Hinkkanen and X. Wang, "Generic PLL-Based Grid-Forming Control," in IEEE Transactions on Power Electronics, vol. 37, no. 2, pp. 1201-1204, Feb. 2022, doi: 10.1109/TPEL.2021.3106045.

Typical wind turbine curve



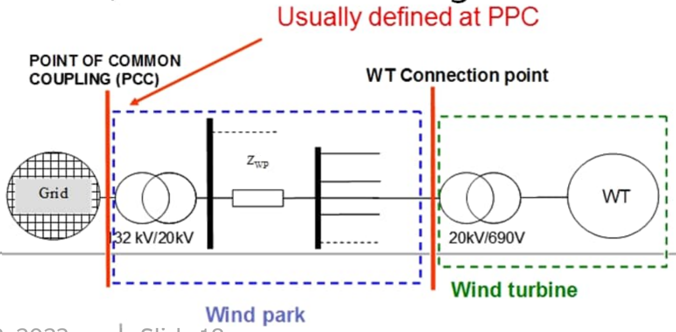
Grid converter operation area



Standards and grid codes

Standards

- Standards define rules for safety, design, installation, operation, and e.g. parameters related to power quality, EMC etc.
- Fulfilling a certain standard maybe a requirement made by public authority
- Standards are specific to area (e.g. IEC in Europe, and IEEE in U.S.)
- Standard may consider a single equipment or a system (installation) connected to the grid



Grid codes

- Grid codes define technical minimum requirements for the power plants connected to the grid
- The content is grid (country/region) specific
  - Depend on the production capacity and the voltage of the connection point

Rated power / Connection point voltage	0,8 kW – < 1 MW	1 MW – < 10 MW	10 MW – < 30 MW	30 MW ≤
U < 110 kV	A[1]	B[1]	C	
110 kV ≤ U	D	D	D	D

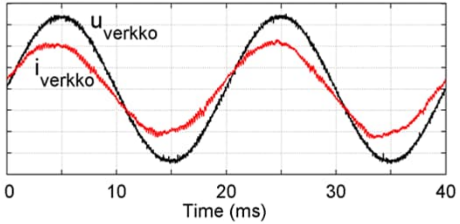
1 Regardless of the connection point's voltage under the connection agreement, the voltage level of the connection point of type A and B power generating facilities is considered to be the voltage level to which the power generating facility's main transformer is connected or the voltage level to which the power generating facility is connected directly without a main transformer

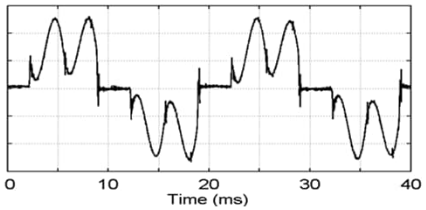
- Define responsibilities and rights of energy producers, consumers and system operators
- Needed to secure safety, stability, efficiency and reliability
- Reflect the structure and status of the transmission system
  - e.g. grid structure, technology used, grid strength, properties of production and consumption

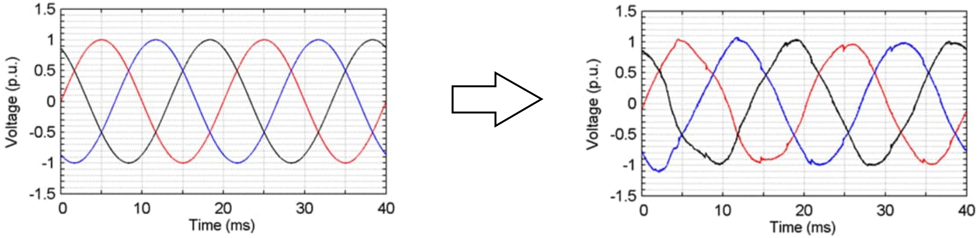
Example of standards

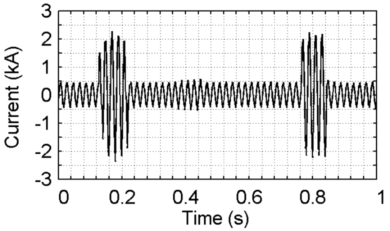
Harmonic standards

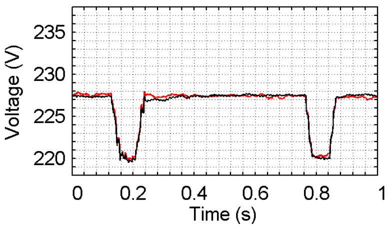
- Harmonics
  - Voltage distortion due to grid impedance
  - Increased power losses
  - Resonance excitation
  - Flicker











Example of standards

Harmonic standards

- Harmonic contents defined as e.g.
  - IEC Standard 61400-21
  - IEEE519
  - Typically harmonic contents report is requested by customer (current/voltage) before ordering

Table 10-3—Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where
I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

Grid codes

Main requirements

- The power generating facility withstands the voltage and frequency fluctuations occurring in the power system
- The power generating facility supports the operation of the power system during disturbance situations, and operates reliably during and after such situations
  - Control of power
  - Control of reactive power
  - Ac-voltage control
  - Low and high voltages during faults
  - Rapid voltage changes
- The power generating facility does not cause any adverse impacts to the other installations connected to the power system
- The relevant network operator and transmission system operator obtains the data on the power generating facility, necessary in the planning of the power system and its operation and in the maintaining of system security.

Nationally, the aim is to ensure security of the supply

Grid code requirements (the most essential ones)

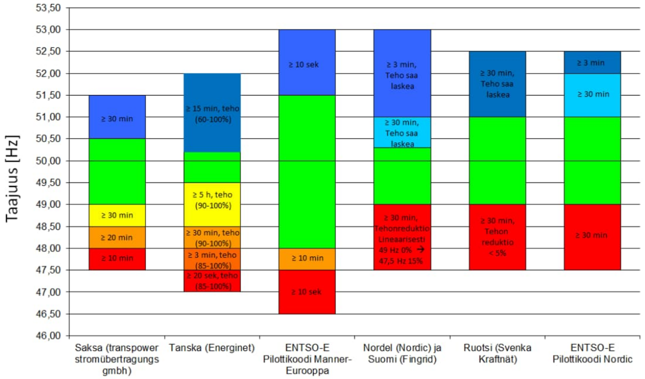
Operational frequency limits and frequency control

Frequency of the power system is a "global" (grid specific) quantity

Frequency reflects the balance between energy production and consumption

Over- and underfrequency e.g. increases thermal stresses in generator windings, reduces life time of insulation

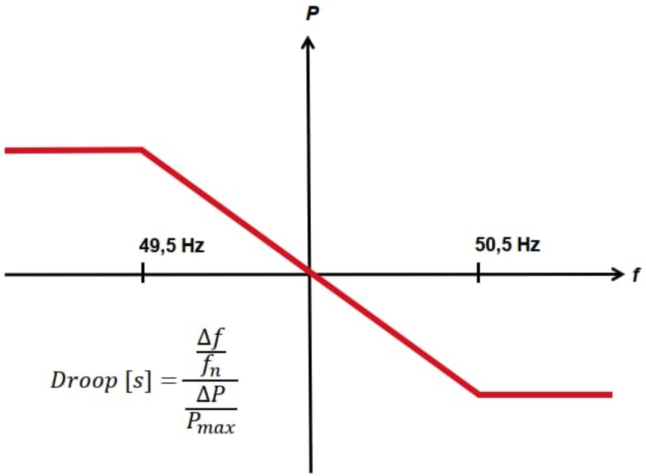
Operational limits*



Kuva 4.1. Kantaverkkoyhtiöiden ja kantaverkkoyhteistyöjärjestöjen vaatimat taajuuden toiminta-alueet tuulivoimaloille. (TRANS 2009; Energinet 2010a; FIN 2009; SvK 2005; NORD 2007; ENTSO-E CODE)

Green color in the fig refers to the normal operation conditions
Other colors define conditions with minimum operational time required

Frequency control



$$Droop\ [s] = \frac{\frac{\Delta f}{f_n}}{\frac{\Delta P}{P_{max}}}$$

*Vainikka J.-P. (2011) "Hajautetun tuotannon verkkoonliittäminen – verkkokoodit ja käytännön toimet", M.Sc thesis, LUT

Grid code requirements (the most essential ones)

Operational limits for frequency

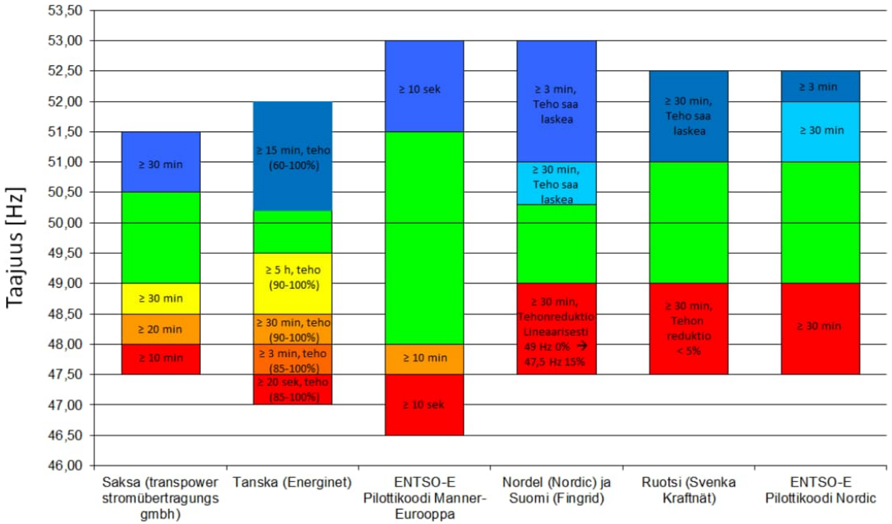
Frequency of the power system is a “global” (grid specific) quantity

Frequency reflects the balance between energy production and consumption

Over- and underfrequency e.g. increases thermal stresses in generator windings, reduces life time of insulation

The figure illustrates operational limits for the frequency

- Green color in the fig refers to the normal operation conditions
- Other colors define conditions with minimum operational time required



Kuva 4.1. Kantaverkkoyhtiöiden ja kantaverkkoyhteistyöjärjestöjen vaatimat taajuuden toiminta-alueet tuulivoimaloille. (TRANS 2009; Energinet 2010a; FIN 2009; SvK 2005; NORD 2007; ENTSO-E CODE)

[Vainikka J.-P. (2011) ”Hajautetun tuotannon verkkoonliittäminen – verkkokoodit ja käytännön toimet”, M.Sc thesis, LUT]

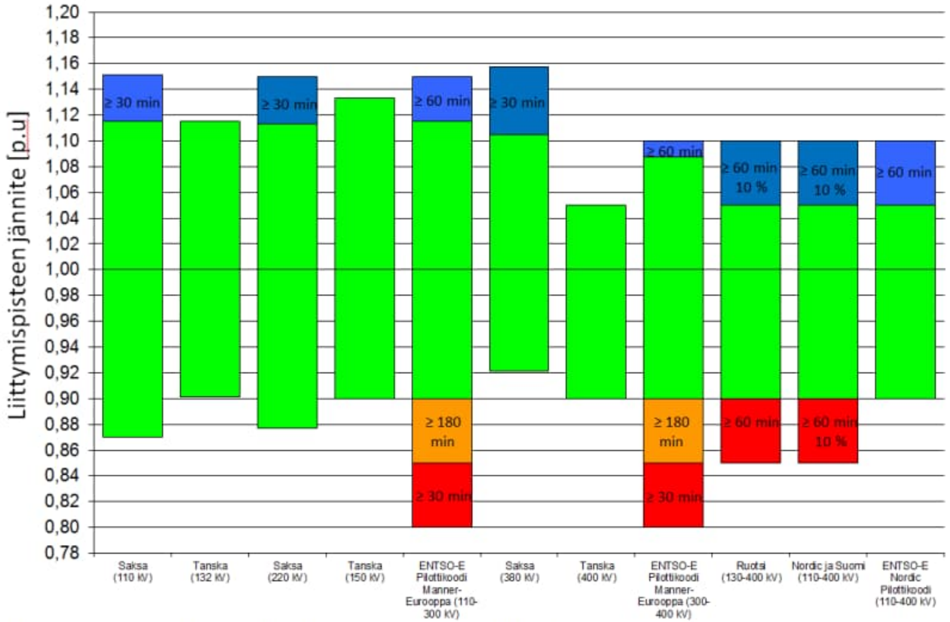
Grid code requirements (the most essential ones)

Operational limits for voltage

In comparison to the frequency, power system voltage can be controlled only locally through reactive power production /consumption

Distributed generation is required to be able to operate within pre-determined voltage conditions

- Green color in the fig refers to the normal operation conditions
- Other colors define conditions with the minimum operational time required



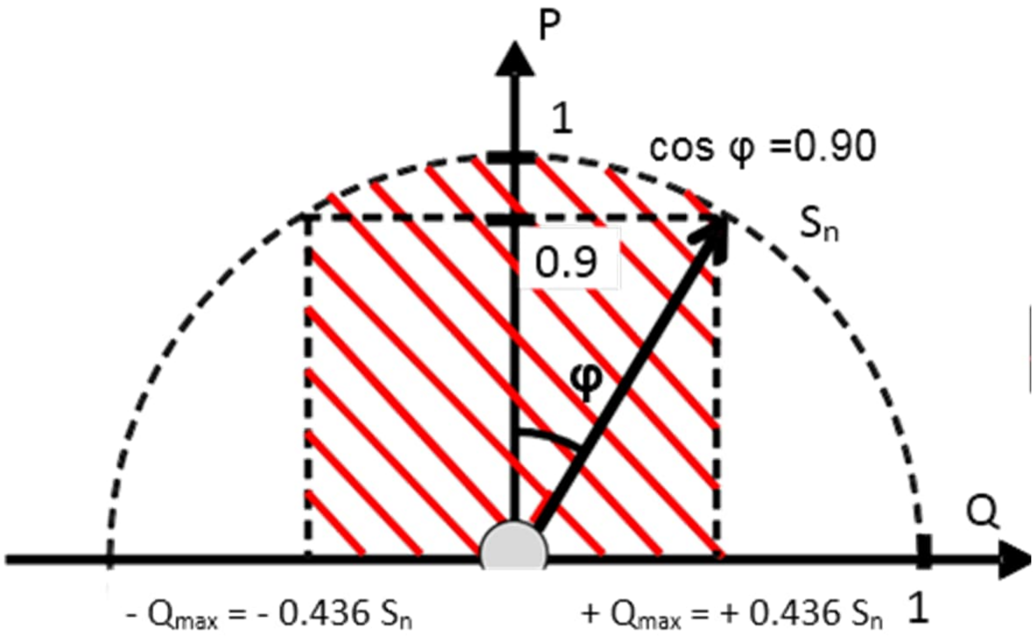
Kuva 4.2. Kantaverkkoyhtiöiden ja kantaverkkoyhteistyöjärjestöjen vaatimat jännitteen toiminta-alueet siirtoverkkoon liitettäville tuulivoimaloille. (TRANS 2009; Energinet 2010a; FIN 2009; SvK 2005; NORD 2007; ENTSO-E CODE)

[Vainikka J.-P. (2011) "Hajautetun tuotannon verkkoonliittäminen – verkkokoodit ja käytännön toimet", M.Sc thesis, LUT]

Grid code requirements (the most essential ones)

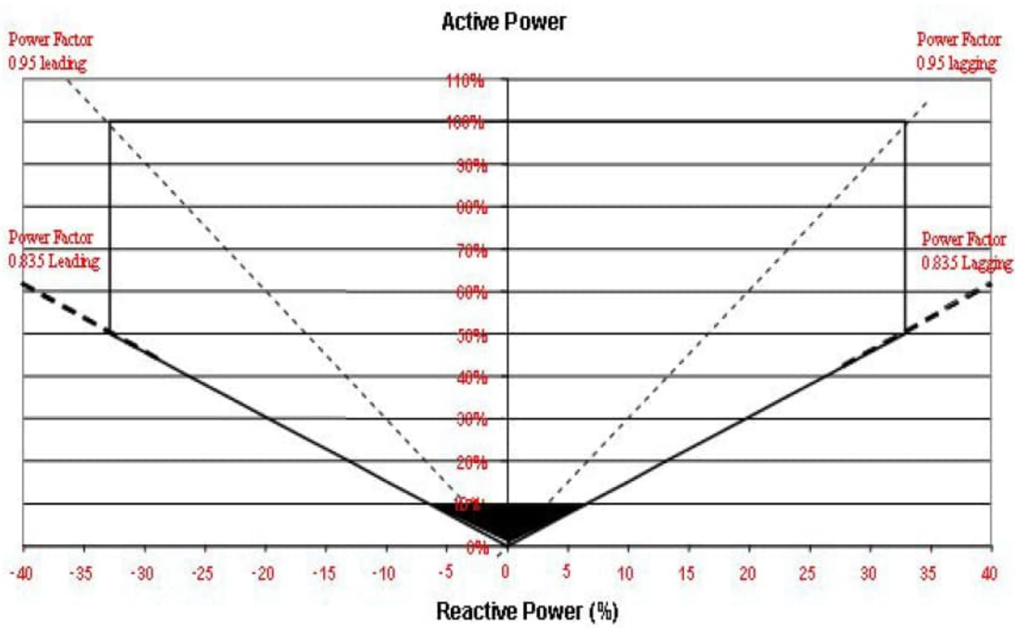
Reactive power production during normal operation

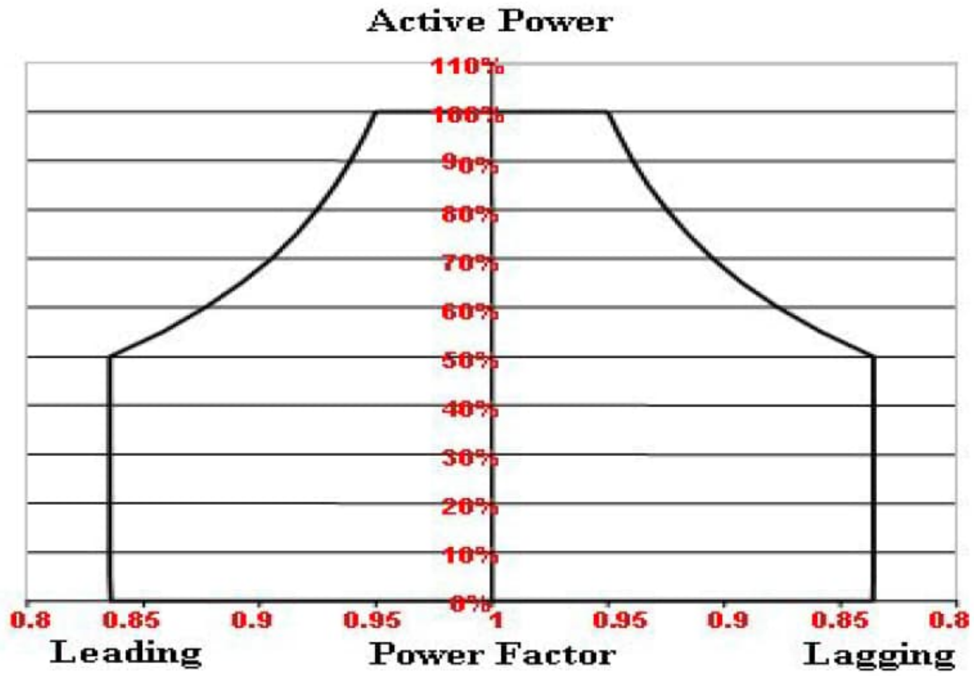
- Reactive power can be used to control the voltage in PCC
  - Reactive power production increases the voltage
  - Reactive power consumption decreases the voltage
- Grid codes typically define power factor
- Typically PQ-curve requested by customer before ordering and performance tested during turbine test campaign



Grid code requirements (the most essential ones)

Reactive power production during normal operation: Example from Ireland grid code v.3.4 (2009)

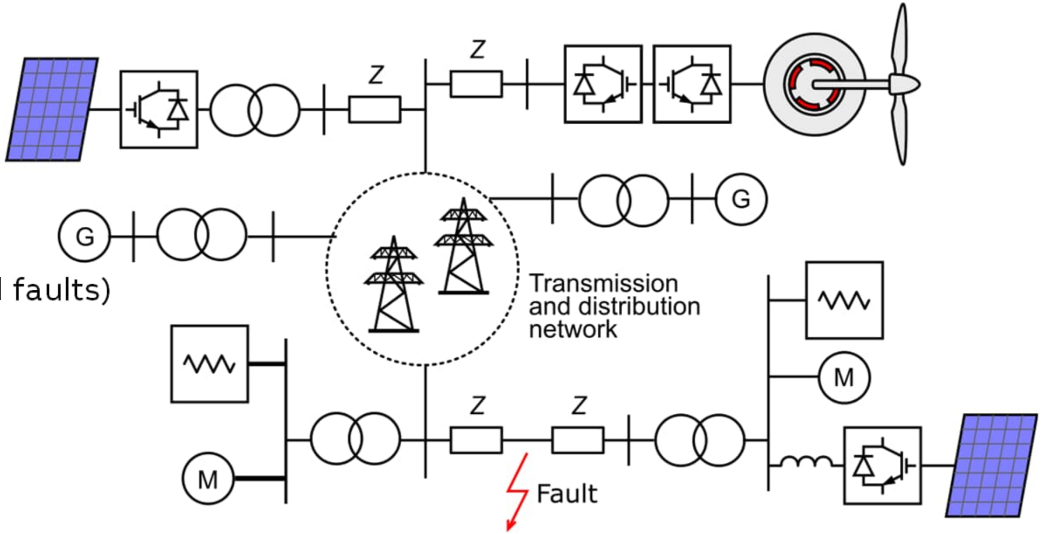




Grid code requirements (the most essential ones)

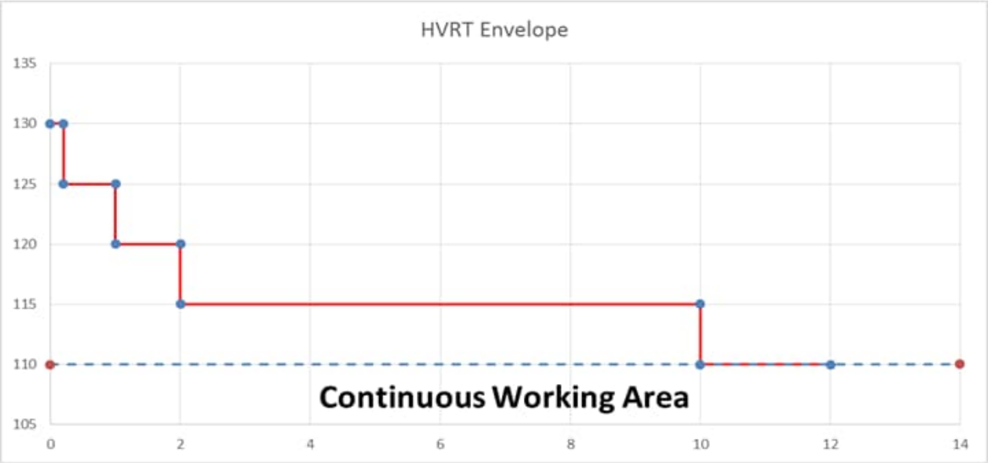
Fault ride through (FRT) – voltage dips and swells

- Temporary changes in voltage level
  - Typical duration 10 ms – 1 min
- Voltage dip: remaining voltage 1 – 90 % nominal voltage
  - Typical depth 10 – 15 %
  - Sources
    - Short-circuit faults in grid (e.g. line-to-line faults, line-to-ground faults)
    - Starting of large (induction) motors
- Voltage swell
  - Sources
    - Lightning strokes
    - Switching operations
    - Sudden load reduction
    - Single-phase short-circuits
    - Non-linearities

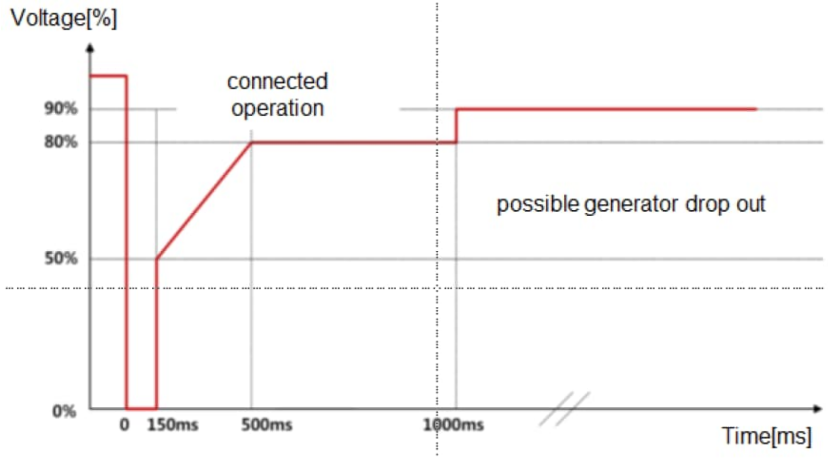


Grid code requirements (the most essential ones)

- Voltage dip (LVRT – low voltage ride through) and voltage swell (HVRT – high voltage ride through) envelopes
  - Define limits within which the converter needs to stay connected
  - Typically tested during turbine FRT (fault ride through) test campaign



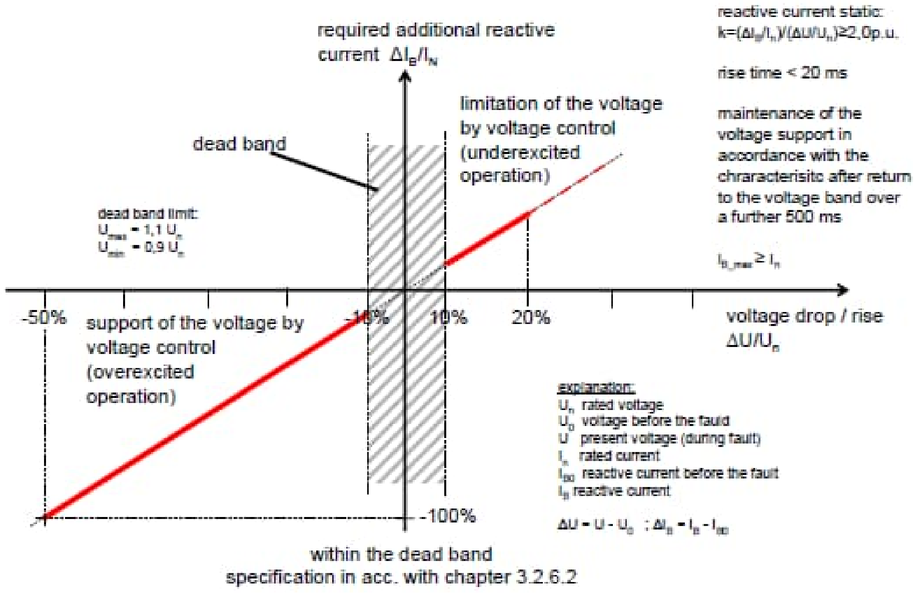
An example of the HVRT envelope



An example of the LVRT envelope

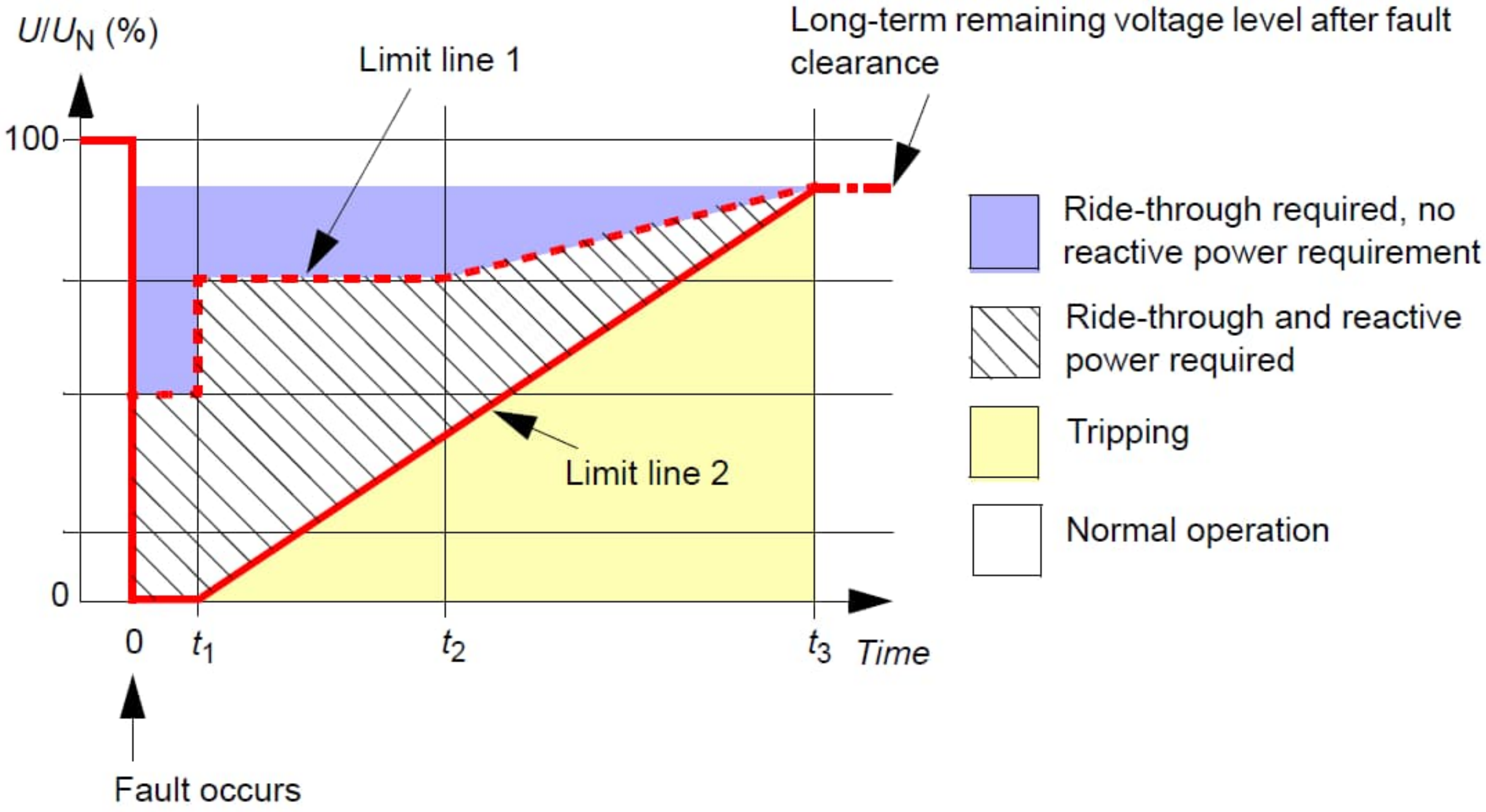
Grid code requirements (most essential ones)

- Essential to support the grid during dips
  - If the power plant disconnects from the grid during dips, the dips may be larger and even grid stability may be affected
- Reactive / active power production during fault ride through (FRT)
  - Typically tested during turbine FRT test campaign

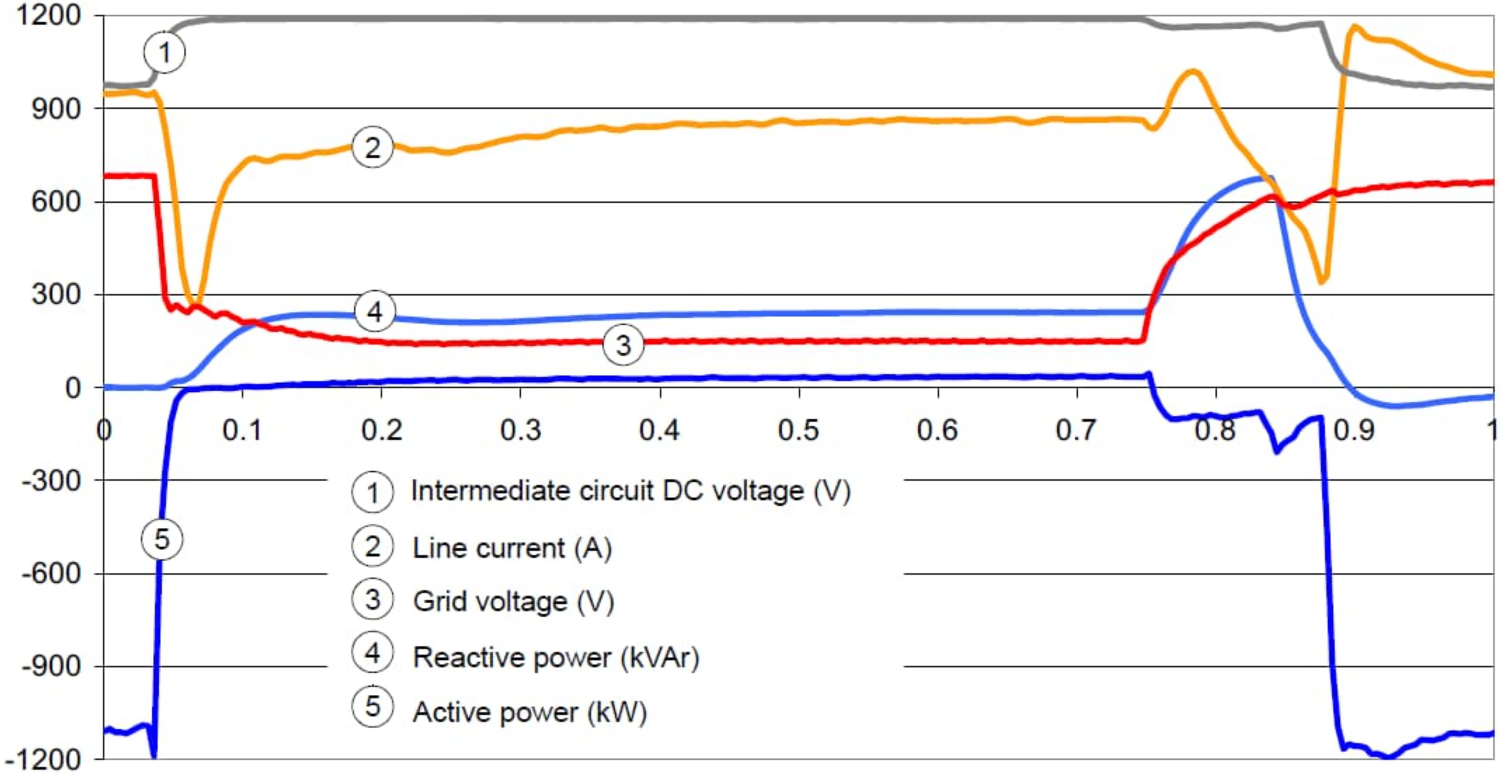


An example of current production during FRT

Grid codes – Fault Ride-Through



Fault Ride-Through – Grid side values



Generator side values depend on the turbine system and converter options (U_{DC} overvoltage control or brake chopper)

Career opportunities for students

Career opportunities at ABB
careers.abb/fi

Your opportunities

Professionals

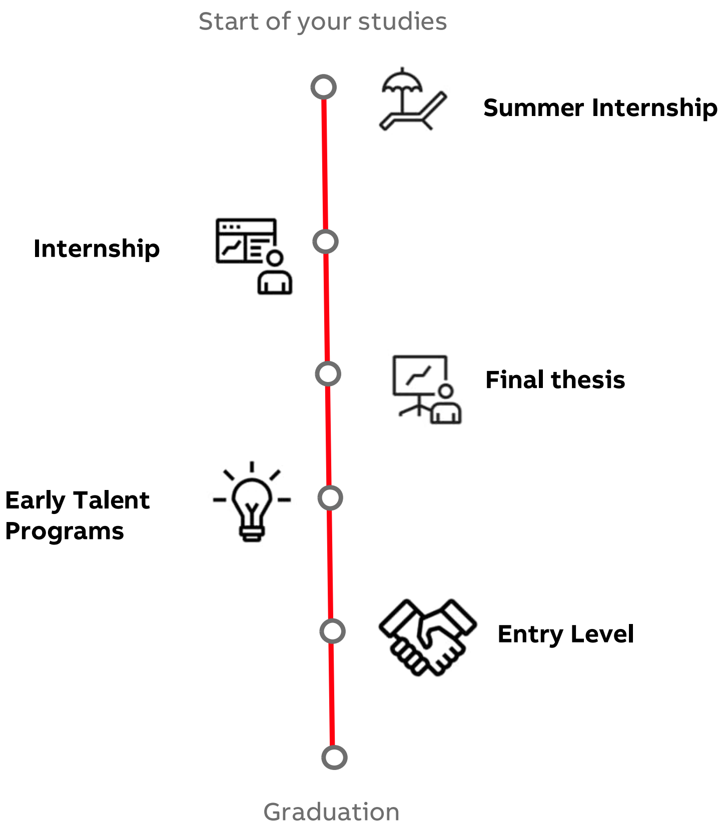
Graduates and entry-level

Students

Skilled Trades

Opportunities for students

careers.abb/fi



Career opportunities at ABB
Students

Summer Internships

- Each year we offer summer internships for up to 800 students from varying study fields.
- Opportunities for in both office and production roles
- The summer internships are mainly located in Helsinki or Vaasa but there are few positions in other locations as well
- The summer job period is mostly between May and September
- Next application period is 3.1.-18.2.2024
- More information on internships and summer jobs at careers.abb/fi ja careers.abb/kesatyo

Internships

- We offer several internship opportunities around the year
- More information: careers.abb/fi

Career opportunities at ABB
Students

Thesis

- For many students, the opportunity to do a thesis opens up in the context of summer work or internships.
- Thesis jobs are mostly found in the following topics:
  - ✓ Electrical engineering
  - ✓ Engineering
  - ✓ Process Technology
  - ✓ Industrial Engineering and Management
  - ✓ Information Technology
  - ✓ Business Administration
- You can leave an open thesis application through the recruitment system at careers.abb/fi . The application is valid for 3 months.

Slide 5

ABB Talent Community

Students

- By joining the ABB Talent Community and allowing notifications, you will get more information regarding our career opportunities for students
- If you in addition create a profile on the careers.abb/fi site, you will get personalized job offers

Slide 6

ABB