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# Power Electronic Converters in Power Systems

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# 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

- What is the main purpose of 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 2019, the total electrical energy production in the world was 27 044 TWh*
  - Wind + solar PV: 2 108 TWh*

**743 GW ≈ 246**

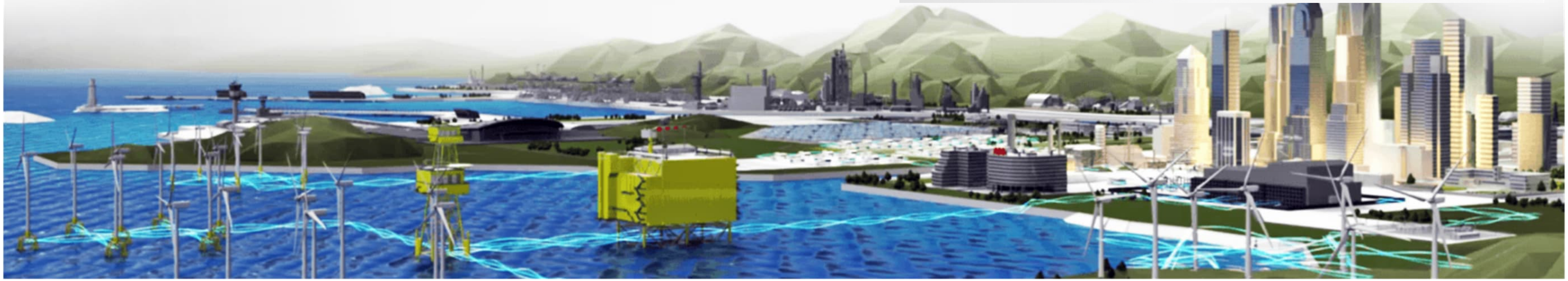
91,9 GW installed in 2020**

The equivalent of 246 nuclear plants

**634 GWp ≈ 211**

116,9 GW installed in 2019***

The equivalent of 211 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/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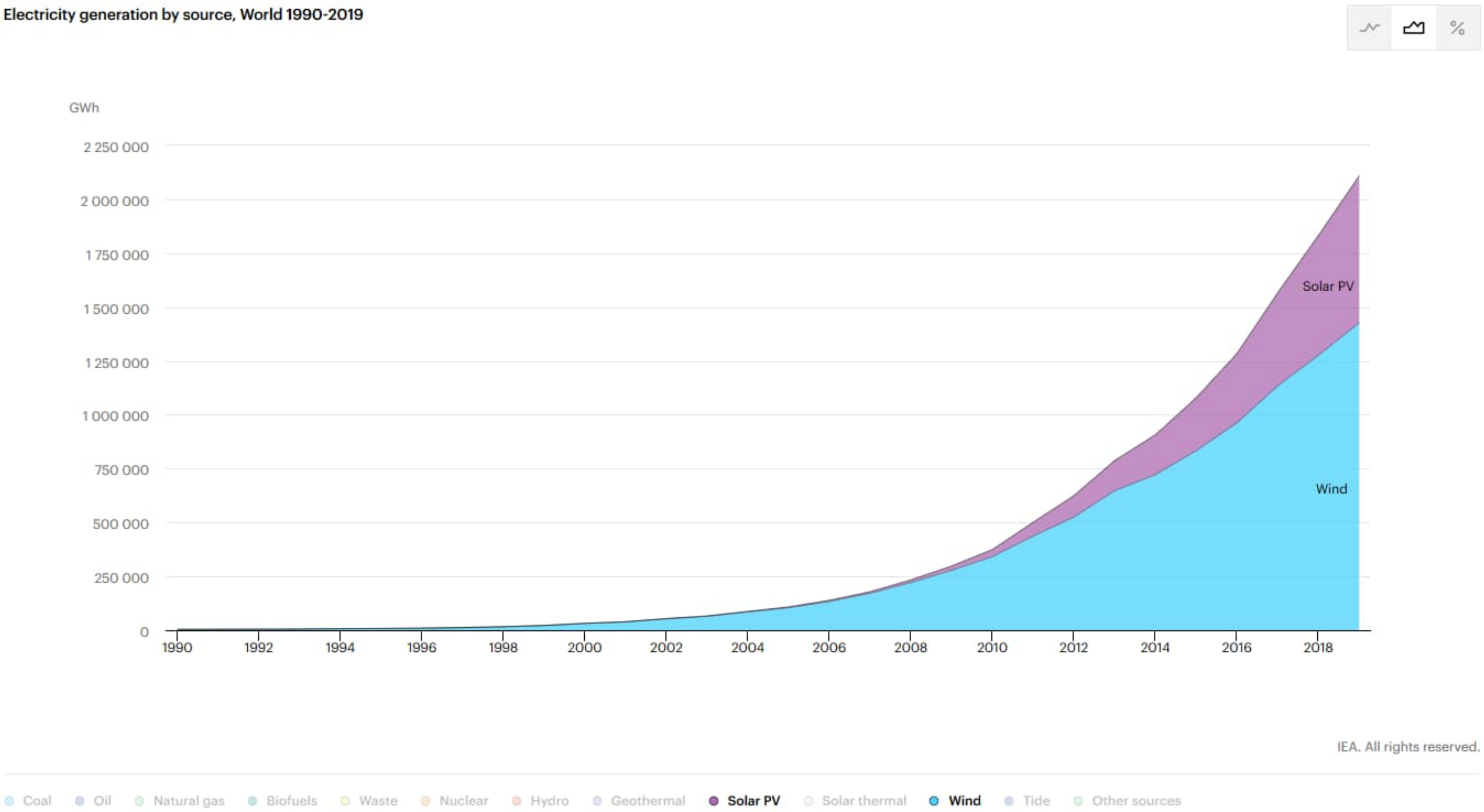
# Electricity generation by source, Wind and Solar PV






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

# Why renewables?

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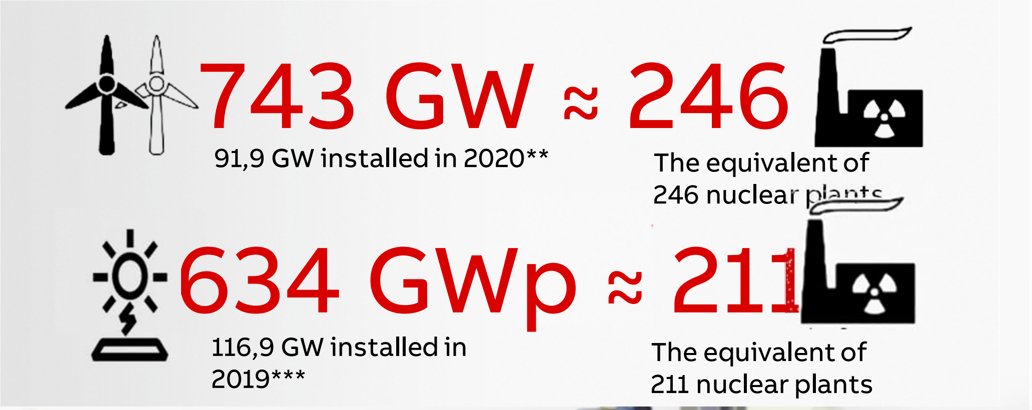
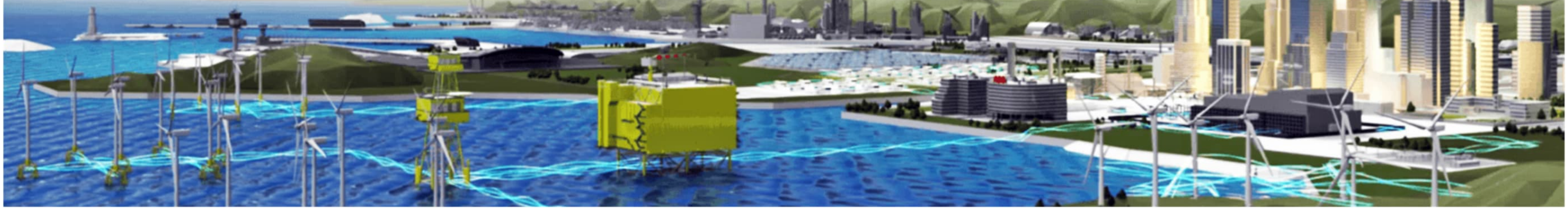
- Today, renewables account for an increasing share of the energy mix and make, in some countries, and important contribution to meeting carbon reduction targets
- Wind and solar power generation can significantly contribute to the big challenge of meeting these growing needs while addressing environmental impact
- In 2019, the total electrical energy production in the world was 27 044 TWh*
  - Wind + solar PV: 2 108 TWh* (7.8 %)
  - Coal: 9 914 TWh* (36.0 %), natural gas 6 346 TWh* (23.4 %), hydro 4 329 TWh* (16.0 %), nuclear 2790 TWh* (10.3 %)



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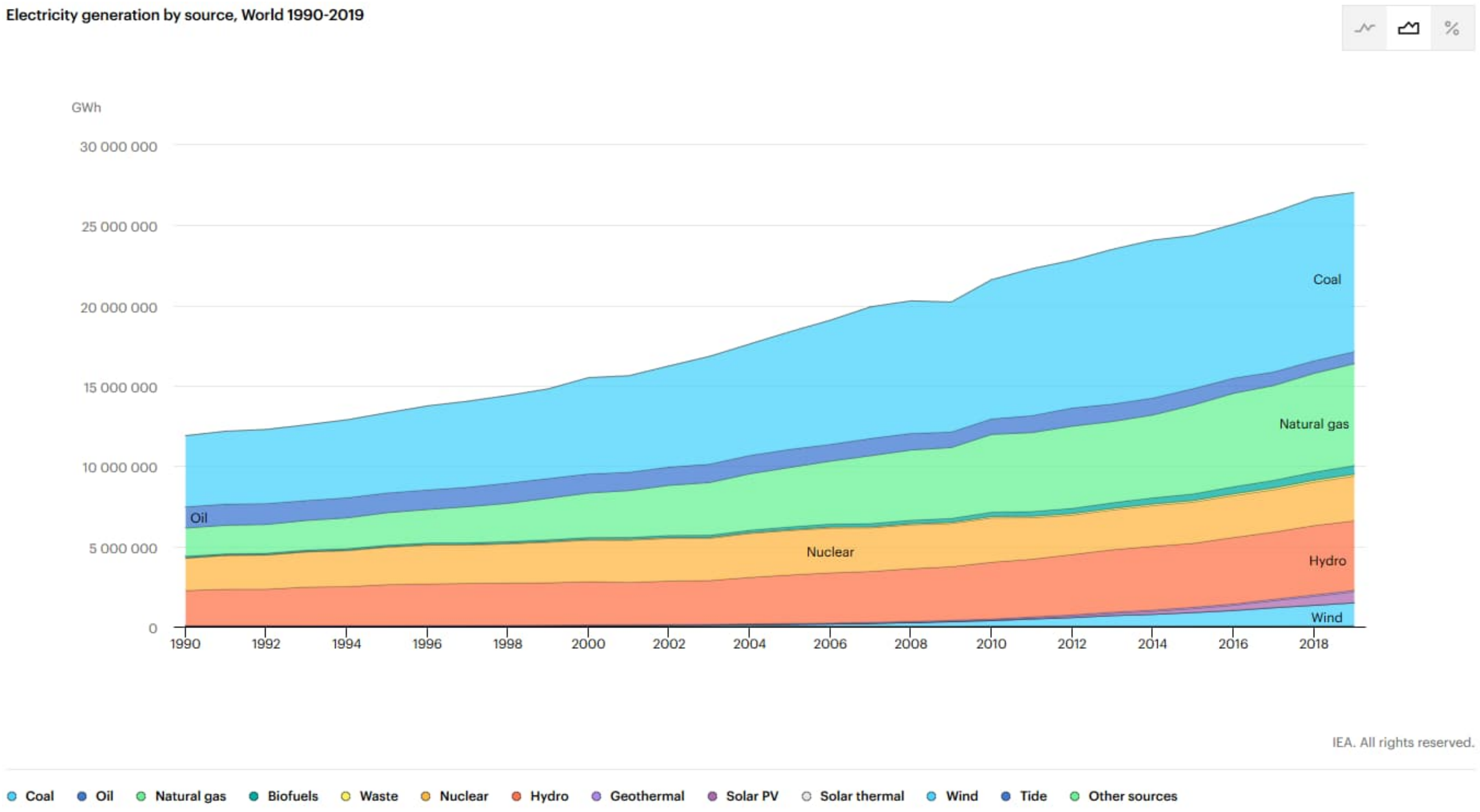
# Electricity generation by source






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

# Control of distributed generation

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

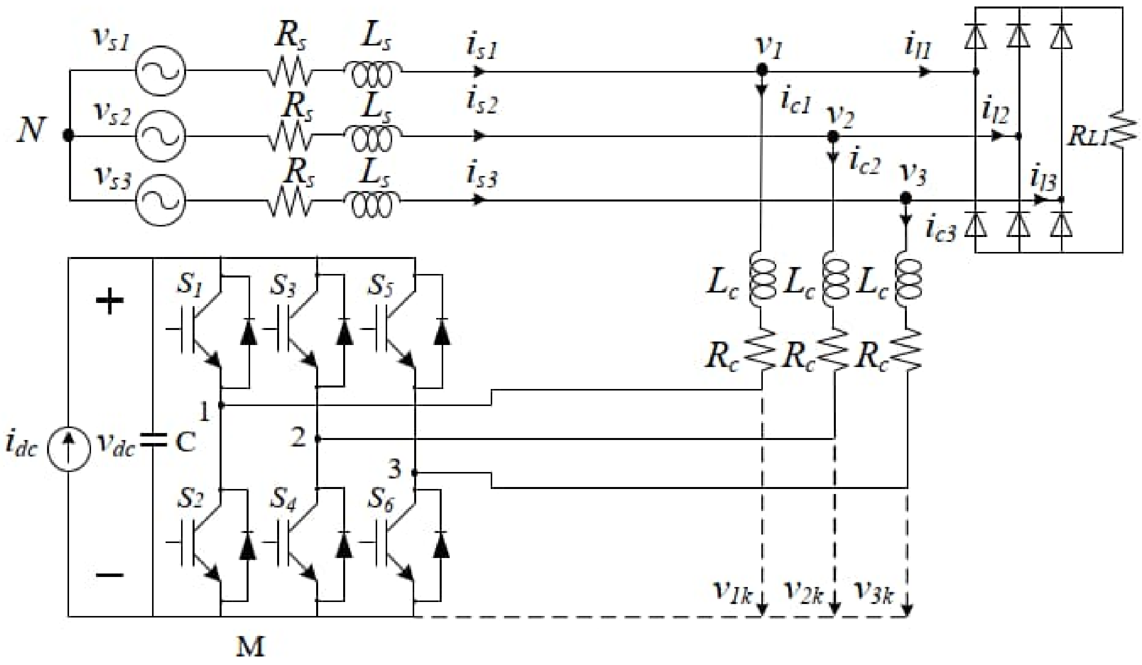



**Fig. 4.1. General model of a grid-connected converter.**

# ABB Products for wind turbines

Wind turbine converters

## Low Voltage Converter

- Onshore or offshore turbines
- IGBT power modules
- Air and liquid-cooled models
- Fault-ride-through
- Reactive power
- Support for different grid codes
- Doubly-fed converter
  - 0.6 to 6 MW
- Full power converter
  - 0.8 to 6 MW

## Medium Voltage Converter

- Onshore or offshore turbines
- IGCT power modules
- 4 to 12 MW
- Liquid-cooled
- Support for different grid codes
- Harmonic elimination control algorithm

# Wind turbine nacelle

# What kind of functionality is needed in order to connect distributed generation to power grid?

Standards and Grid Codes

# Renewables and distributed generation in power systems

Renewable energy sources and distributed generation is connected to the power system through power electronic converters

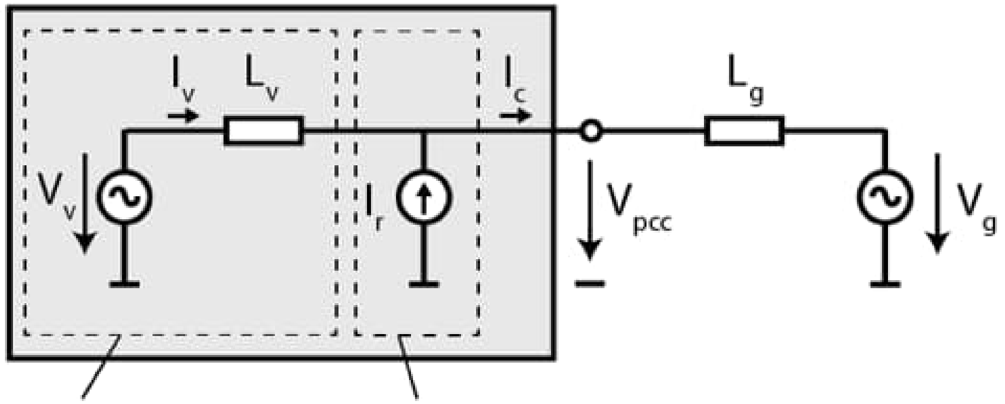
- Electrical characteristics of power electronic converter is completely different from the traditional (rotating) generators
  - Controlled current or voltage sources vs. synchronous machine with back emf
  - EMI and EMC
  - Operation during faults?
    - Fault current capacity
    - Disconnection?

→ **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

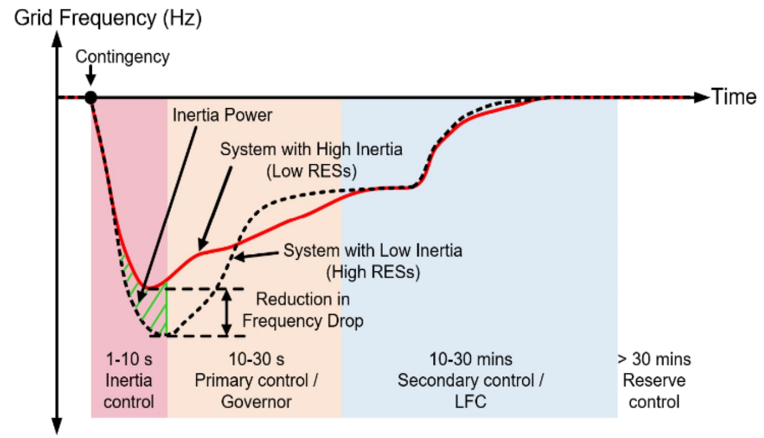



Voltage source behind impedance instead of standard stiff current control

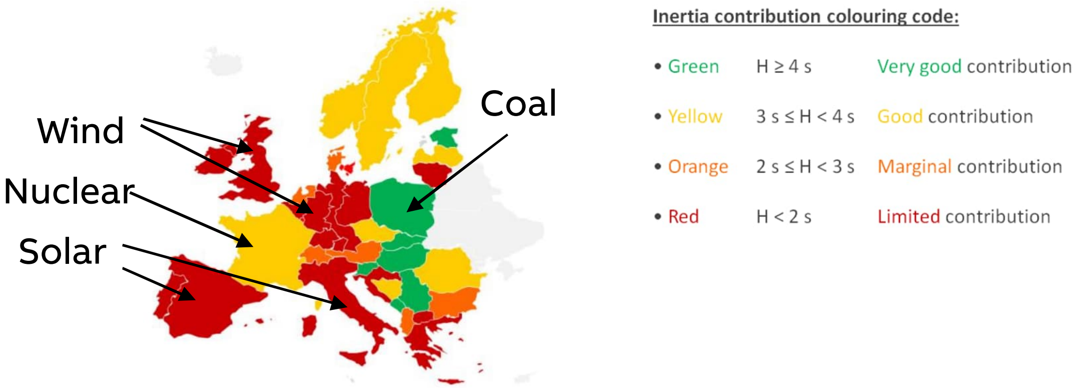
# Renewables and distributed generation in power systems

Increase in the amount of distributed generation in comparison with traditional generation brings new challenges

- Generation changes from rotating machines to power electronics based systems
  - Characteristics of the generators is different. E.g. inertia in power system is reduced
- Limited fault current capacity
  - protection issues
- Unpredictable energy production
  - energy storages, demand response
- Sink for harmonics
- Sink for unbalance
- Creation and responsibility of the system voltage and frequency
  - “Grid forming control” instead of “Grid following 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)*

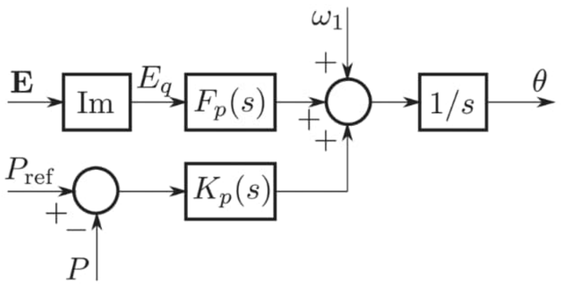


* ENTSO-E Technical Report “High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters”, 2018

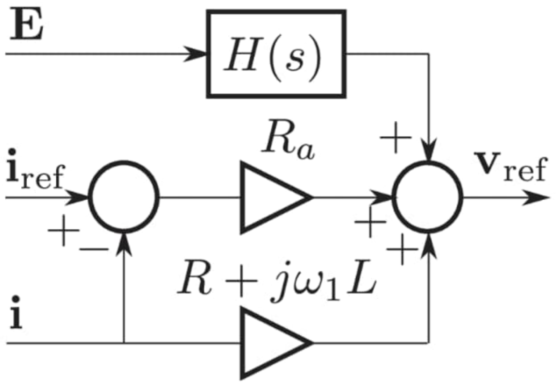
# Control of distributed generation

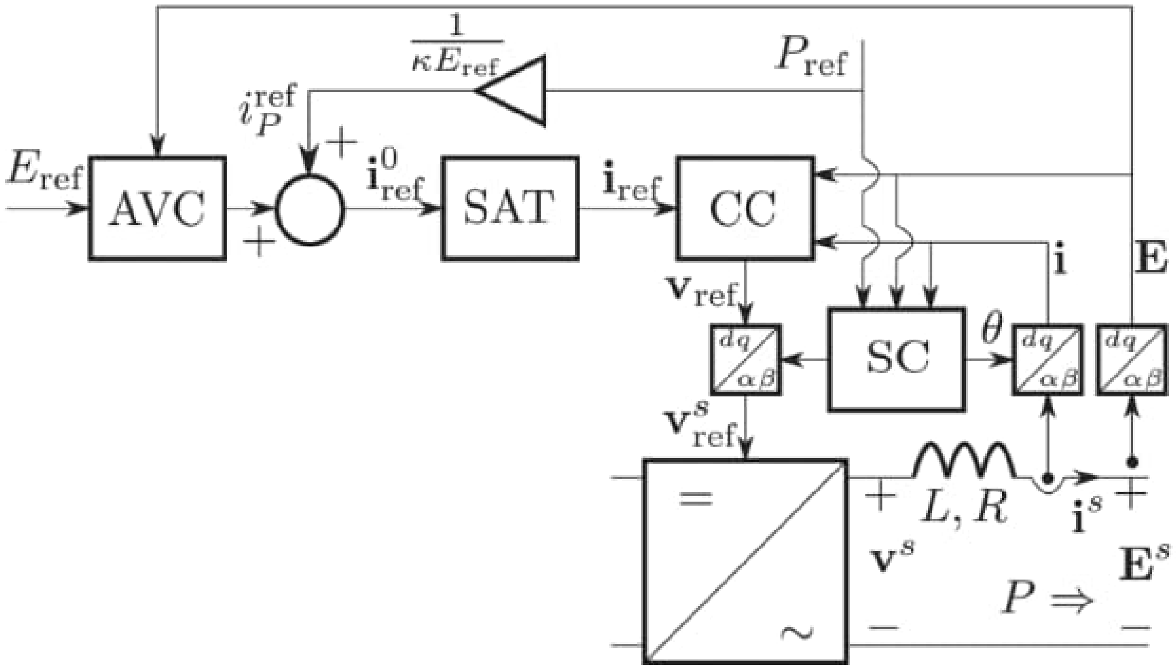
## Control System

### SC – Synchronization controller

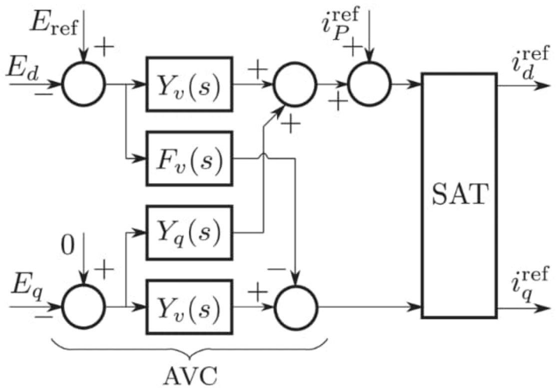



### CC – Current controller




### AVC – AC-voltage controller

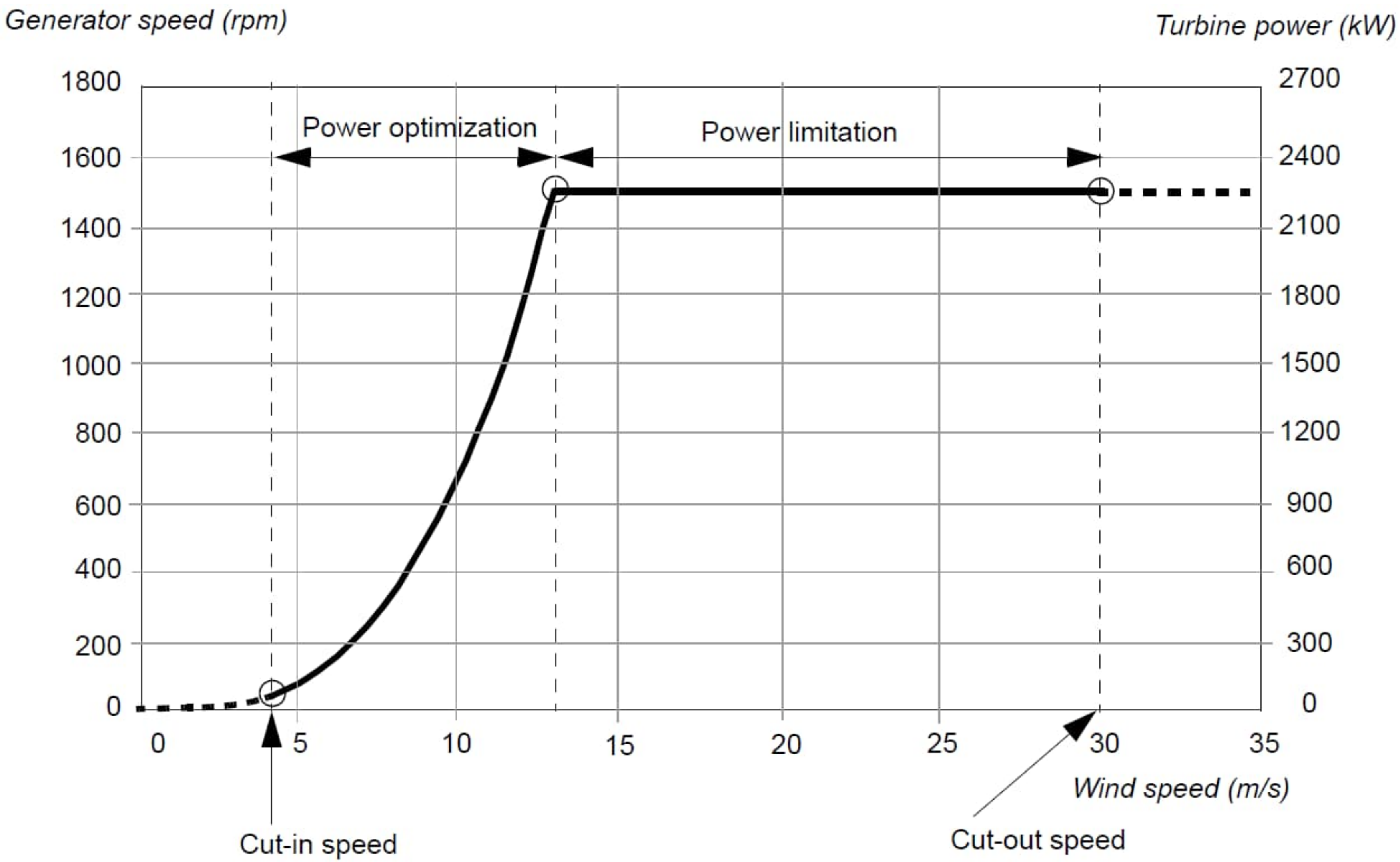




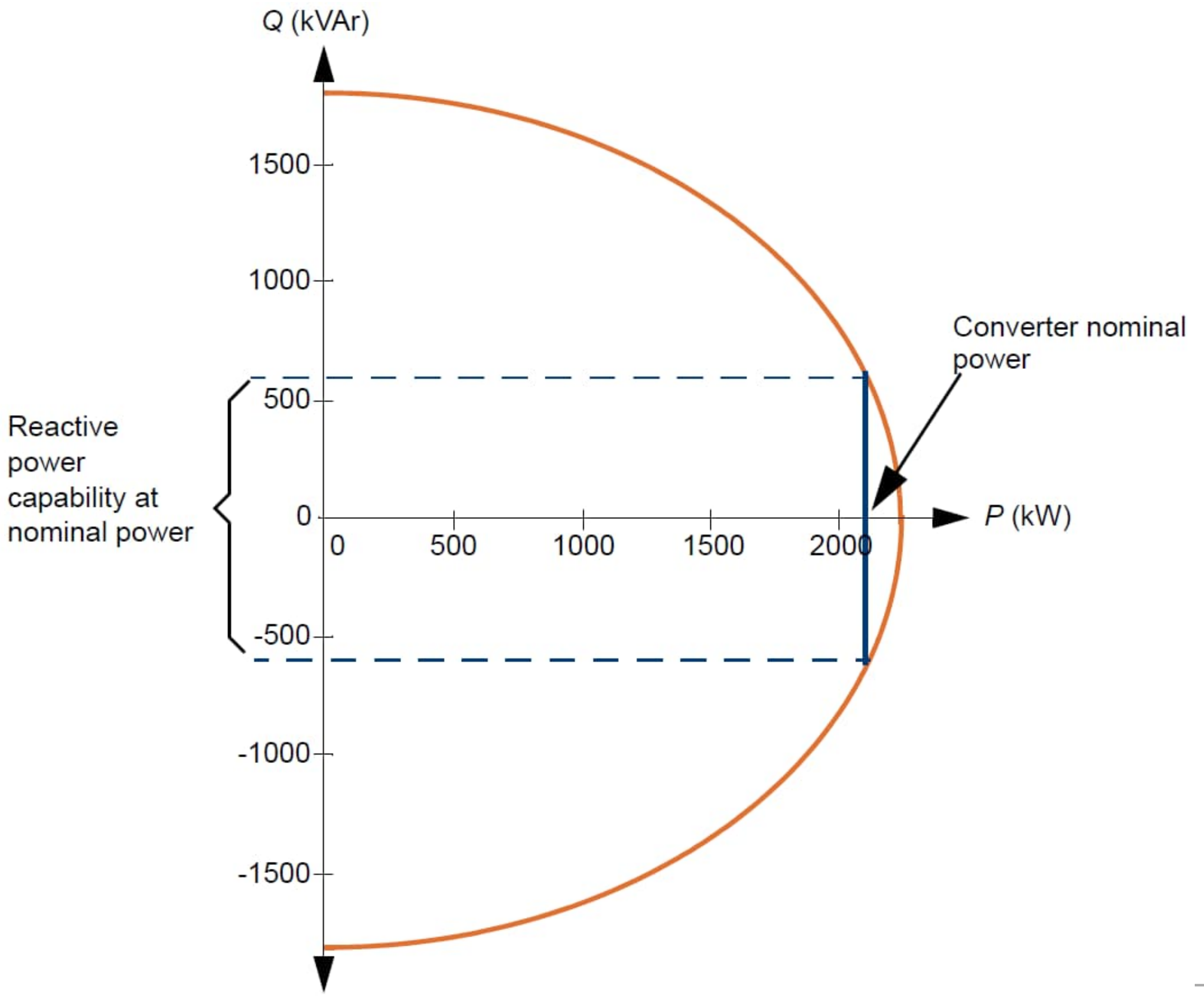


L. Harnefors, M. Schweizer, J. Kukkola, M. Routimo, M. Hinkkanen and X. Wang, "Generic PLL-Based Grid-Forming Control," in IEEE Transactions on Power Electronics, vol. 37, no. 2, pp. 1201-1204, Feb. 2022, doi: 10.1109/TPEL.2021.3106045.

# Typical wind turbine curve



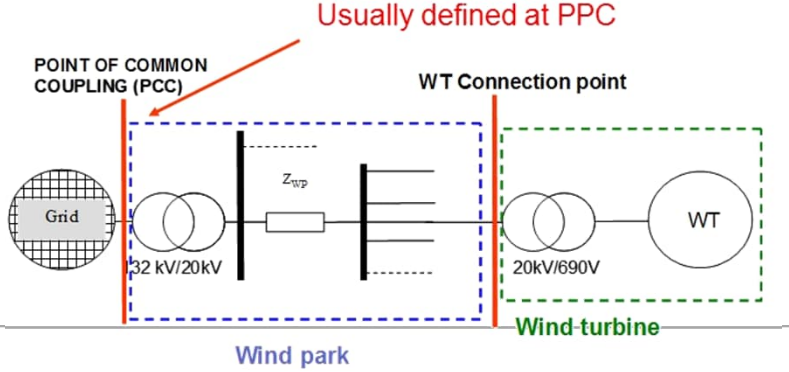
# Grid converter operation area



# Standards and grid codes

## Standards

- Standards define rules for safety, design, installation, operation, and e.g. parameters related to power quality
- 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 |

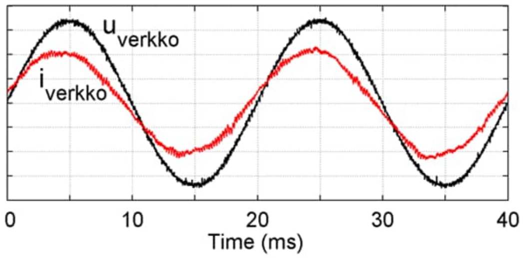
1 Regardless of the connection point's voltage under the connection agreement, the voltage level of the connection point of type A and B power generating facilities is considered to be the voltage level to which the power generating facility's main transformer is connected or the voltage level to which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

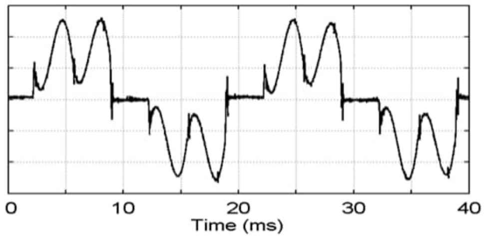
- Define responsibilities and rights of energy producers, consumers and system operators
- Needed to secure safety, stability, efficiency and reliability
- Reflect the structure and status of the transmission system
  - e.g. grid structure, technology used, grid strength, properties of production and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

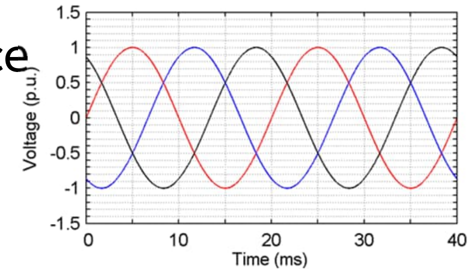
# Example of standards

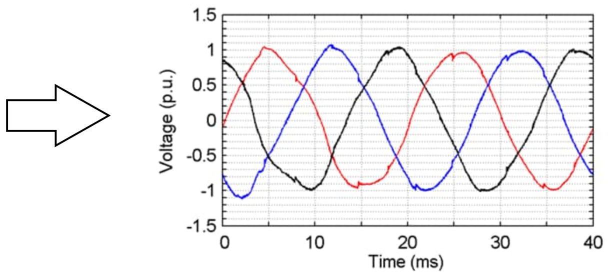
## Harmonic standards

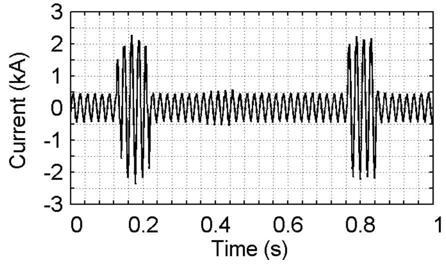
- Harmonics
  - Voltage distortion due to grid impedance
  - Increased power losses
  - Resonance excitation
  - Flicker

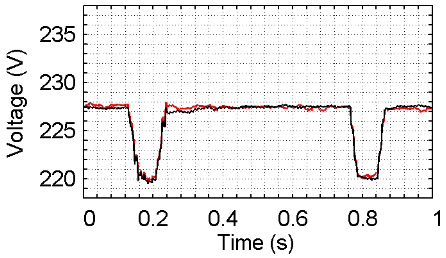


# Example of standards

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)

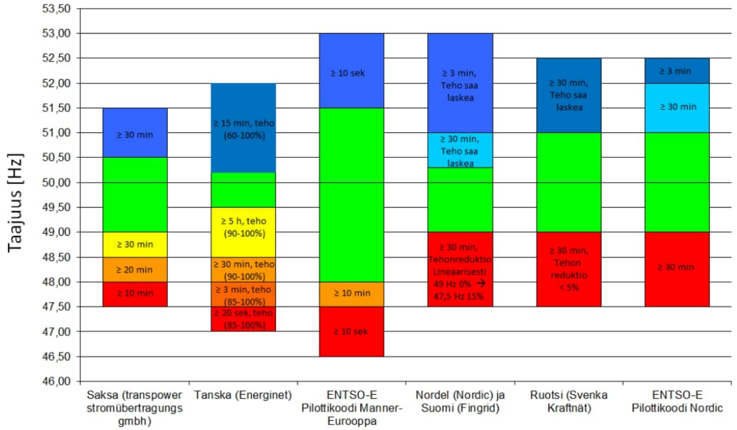
## Operational frequency limits and frequency control

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

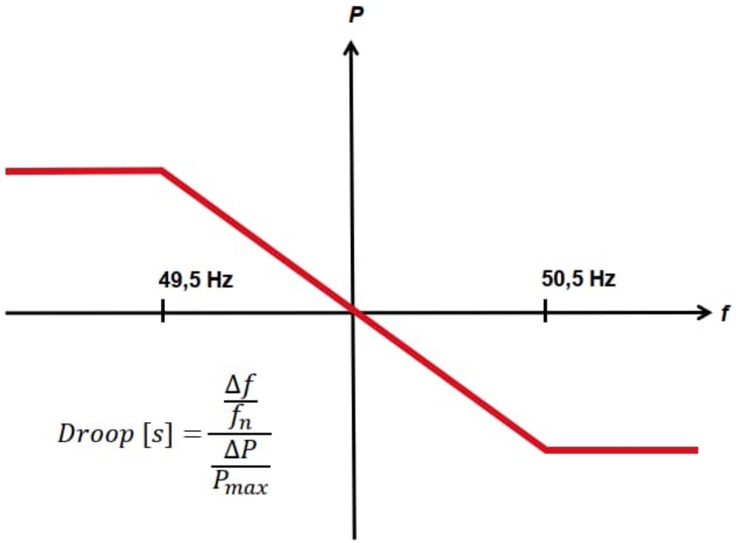
### Operational limits*




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

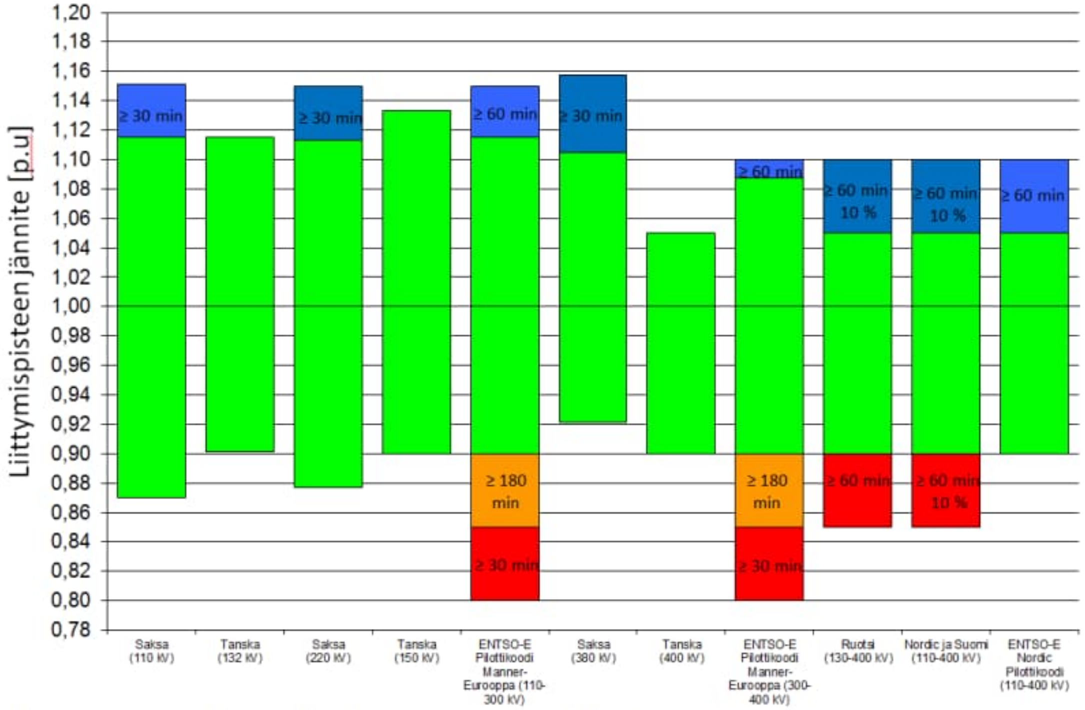
# Grid code requirements (the most essential ones)

## Operational limits for 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



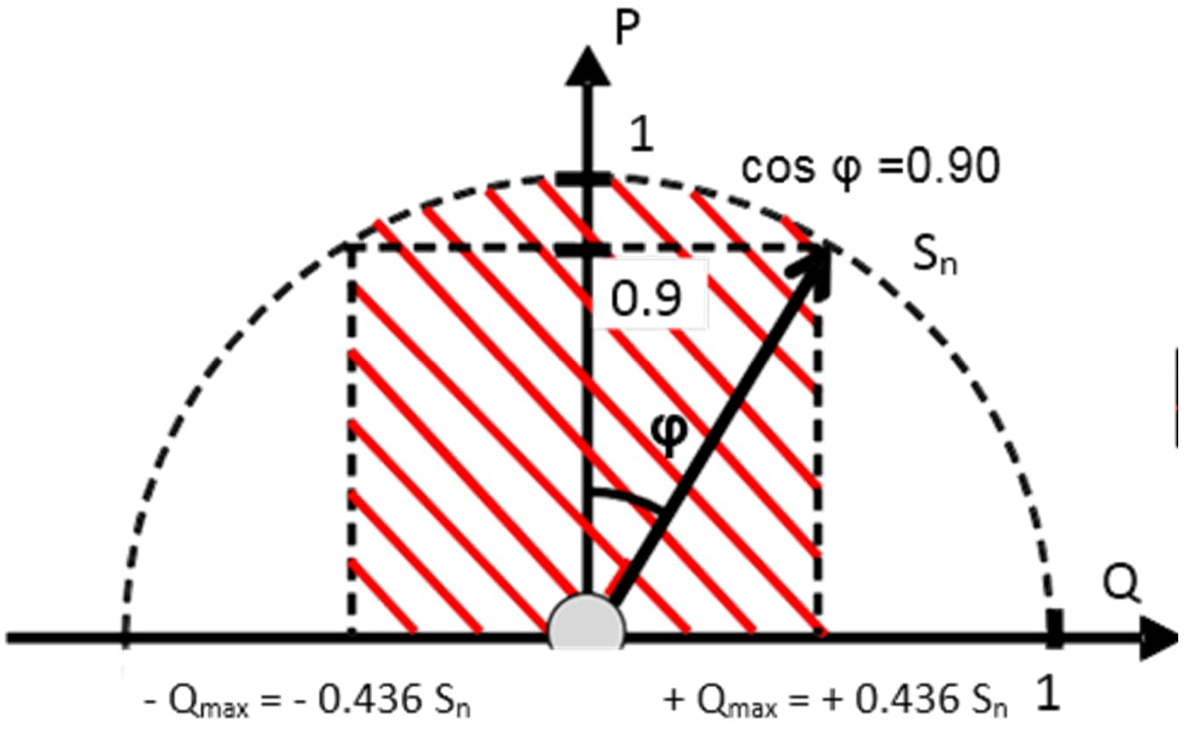

Kuva 4.2. Kantaverkkoyhtiöiden ja kantaverkkoyhteistyöjärjestöjen vaatimat jännitteen toiminta-alueet siirtoverkkoon liitettäville tuulivoimaloille. (TRANS 2009; Energinet 2010a; FIN 2009; SvK 2005; NORD 2007; ENTSO-E CODE)

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

# Grid code requirements (the most essential ones)

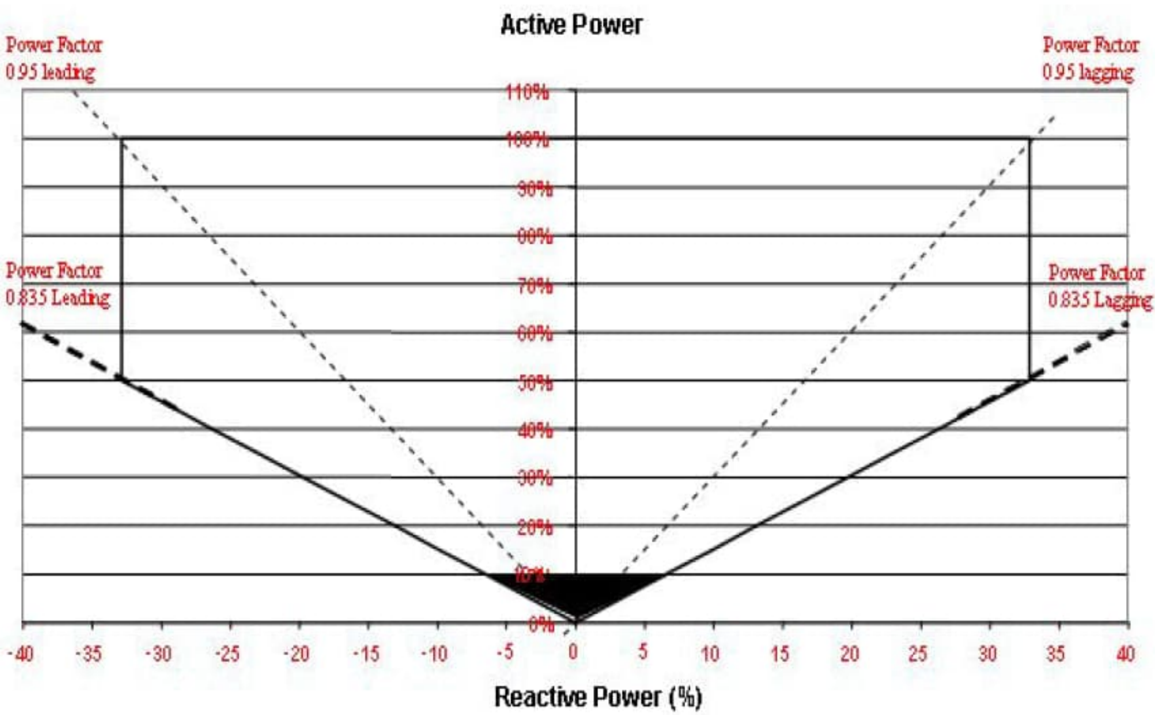
Reactive power production during normal operation

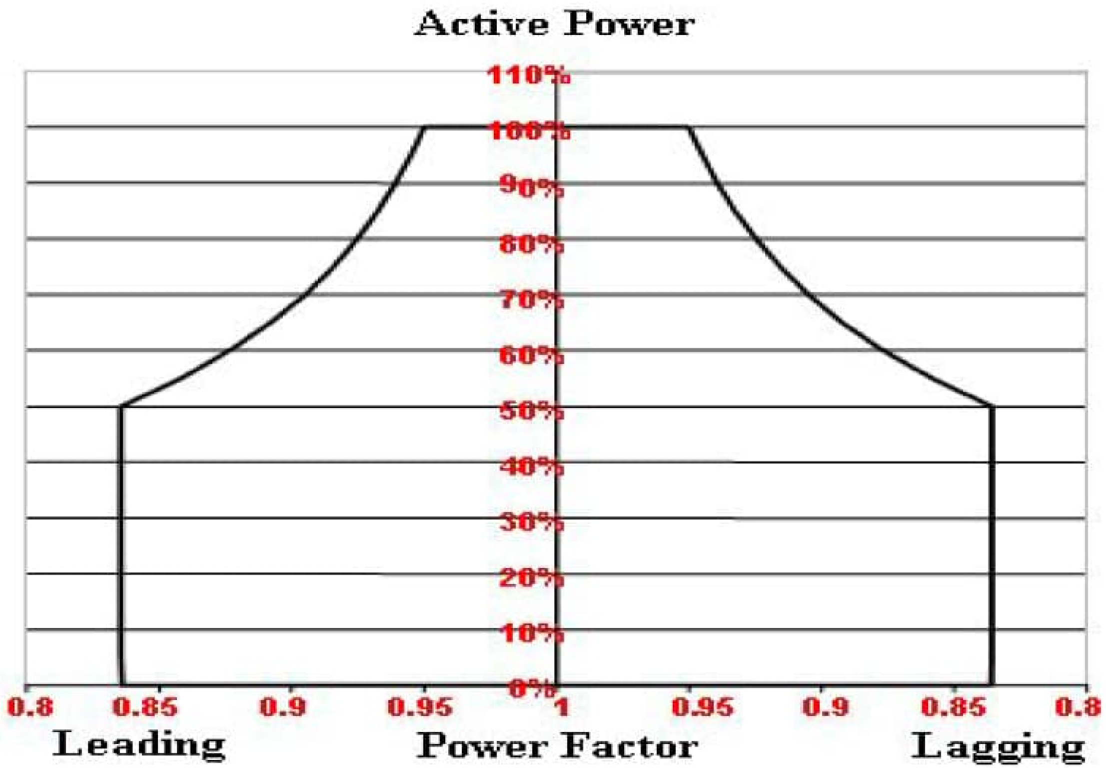
- Reactive power can be used to control the voltage in PCC
  - Reactive power production increases the voltage
  - Reactive power consumption decreases the voltage
- Grid codes typically define power factor
- Typically PQ-curve requested by customer before ordering and performance tested during turbine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



# Grid code requirements (the most essential ones)

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

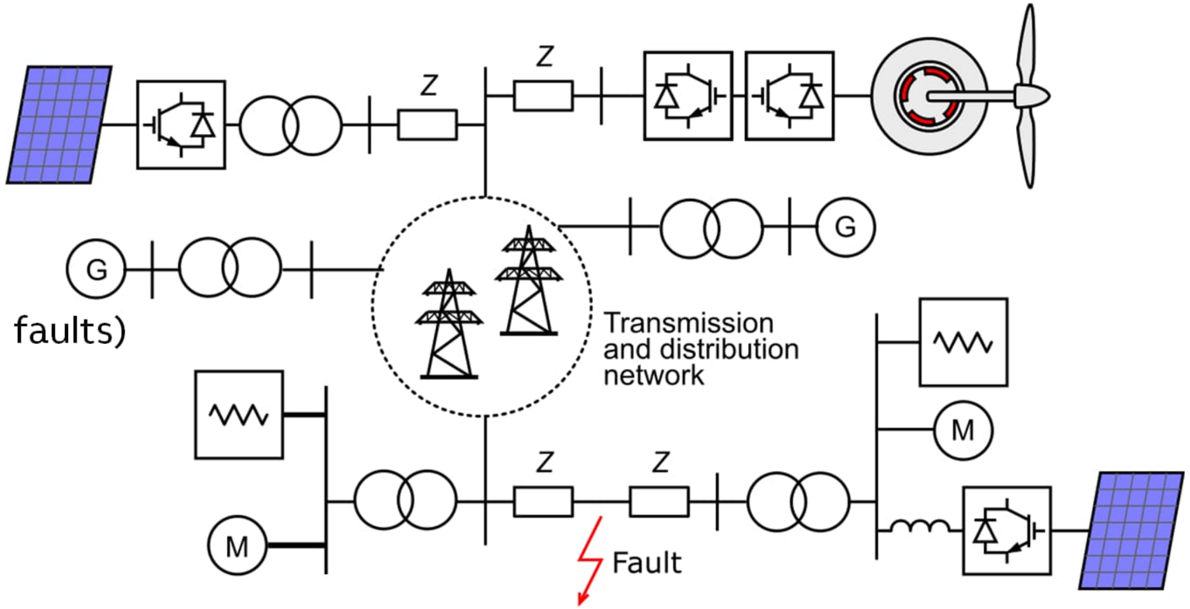


# Grid code requirements (the most essential ones)

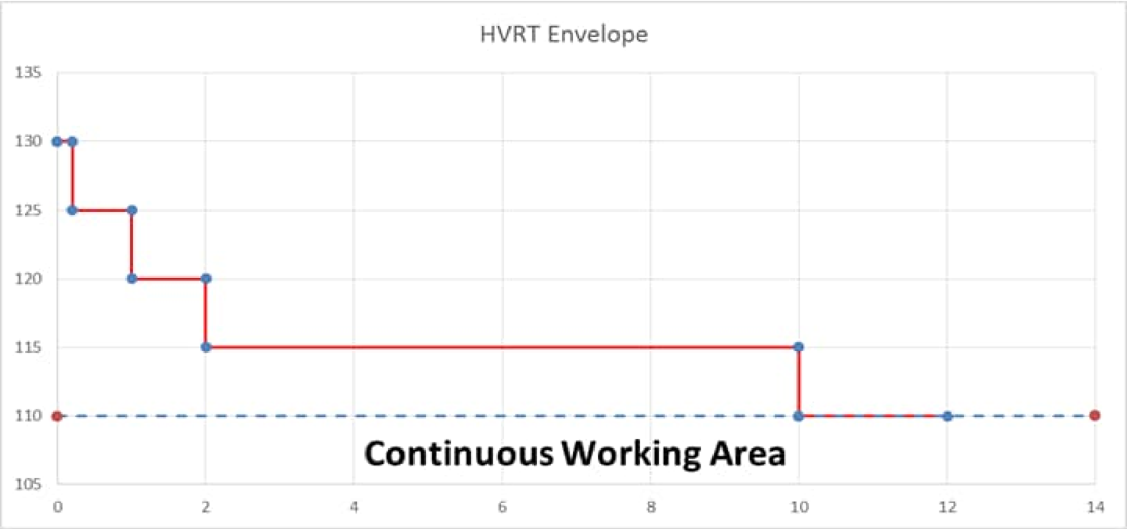
## Fault ride through (FRT) – voltage dips and swells

- 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

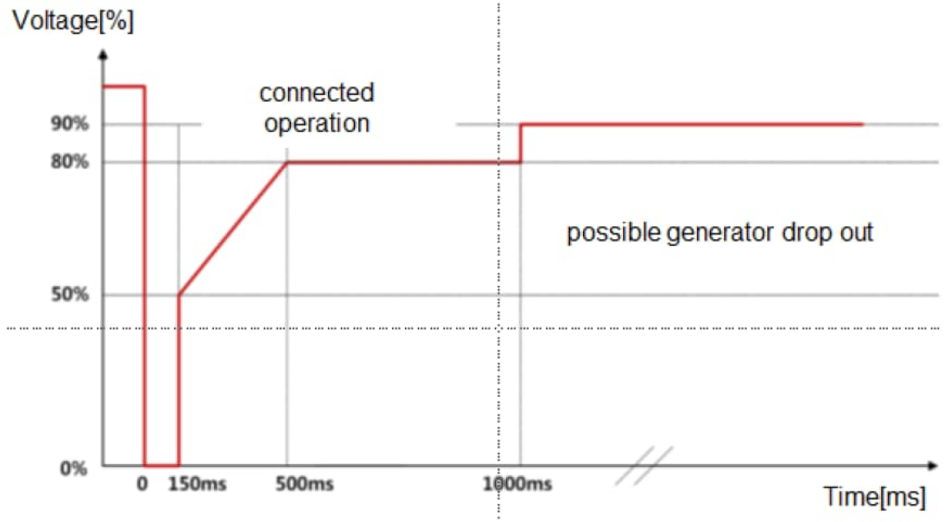


# Grid code requirements (the most essential ones)

- 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



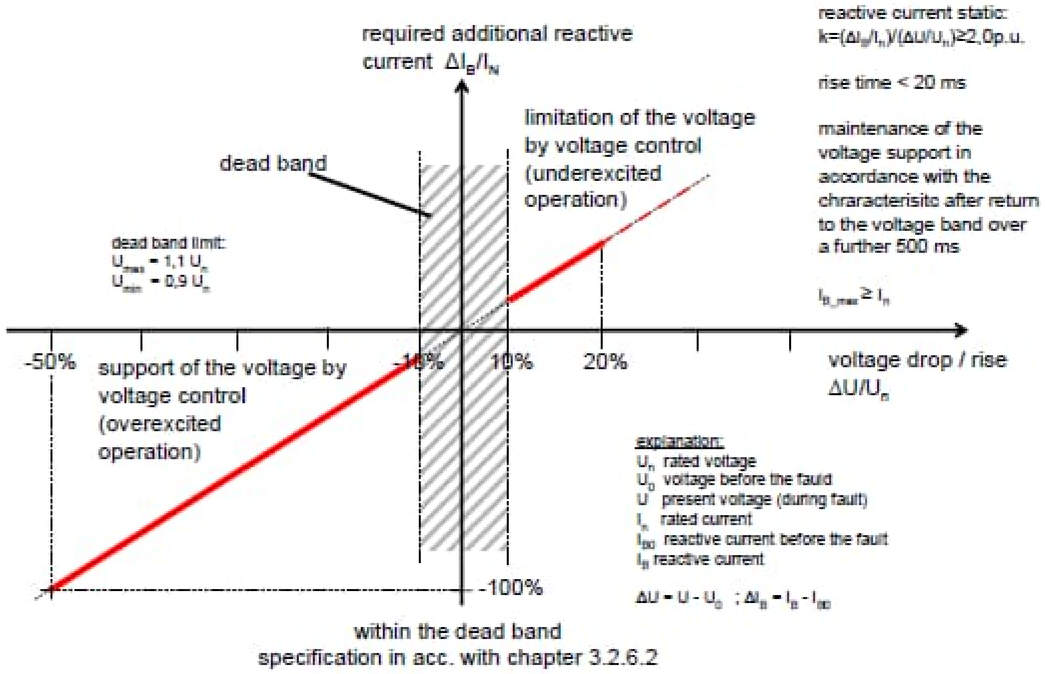

An example of the HVRT envelope




An example of the LVRT envelope

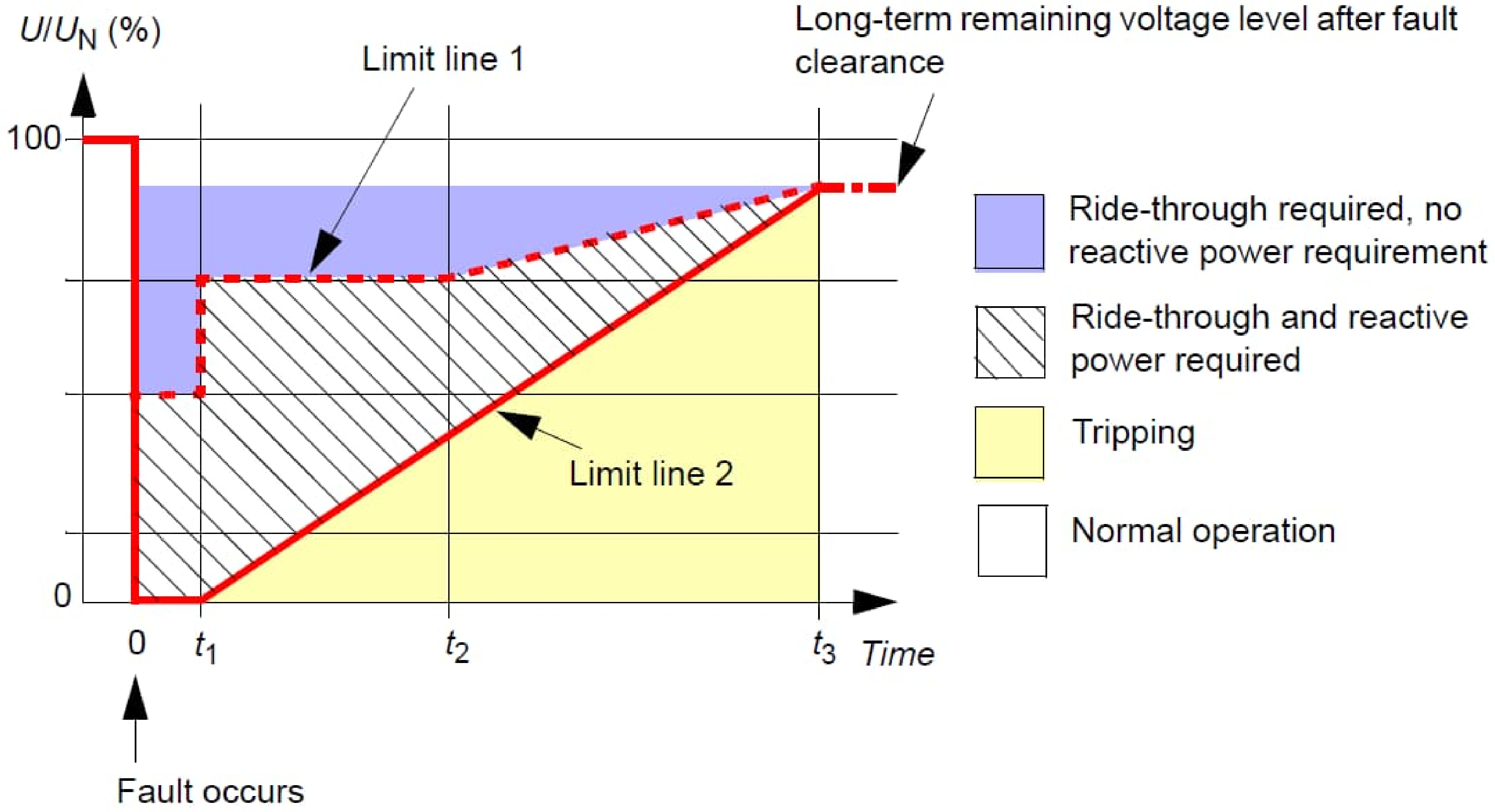
# Grid code requirements (most essential ones)

- 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

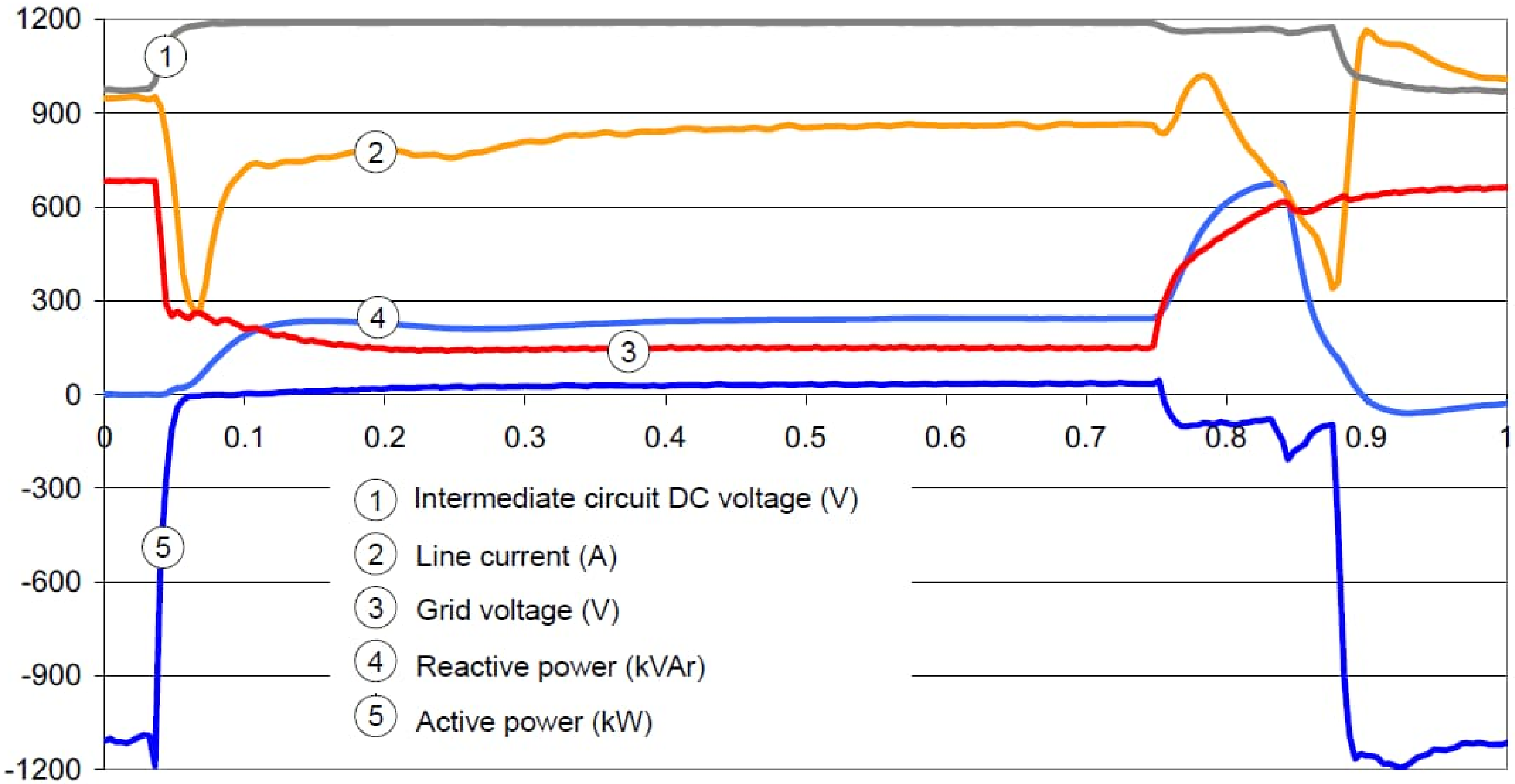



An example of current production during FRT

# 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)

# Simulations

# Simulations

In renewables business different operators have different needs to simulations

– Converter manufacturer, turbine manufacturer, park investor, transmission system operator (TSO)

Converter manufacturer

- FW development and verifications
  - Converter behaviour can be verified in cases that cannot be (easily) captured in automated tests or before doing testing with the actual converter
    - PQ testing
    - FRT testing (voltage dips, swells and sequences of the two)
    - Weak grid operation
    - Grid resonances
    - Switching events (e.g. compensators, auto-reclosure)

# Simulations

System level simulations (transmission system owner, park investor)

- Grid faults and disturbances simulations
- Grid code compliance studies
- Stability studies
- Wind park grid integration studies, eg. SSCI (sub synchronous control interactions)

Turbine manufacturer

- Wind turbine manufacturers incorporate the converter model into their turbine simulation model and use it for their own studies
- Drive train stress studies
- Field problem solving
- Verification of FW-specification phase: Turbine OEM verifies that converter FW fulfils the functional specification

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