Demystifying System Strength and Voltage Stability in Evolving Power Systems

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citations?user=jCGJj2oAA
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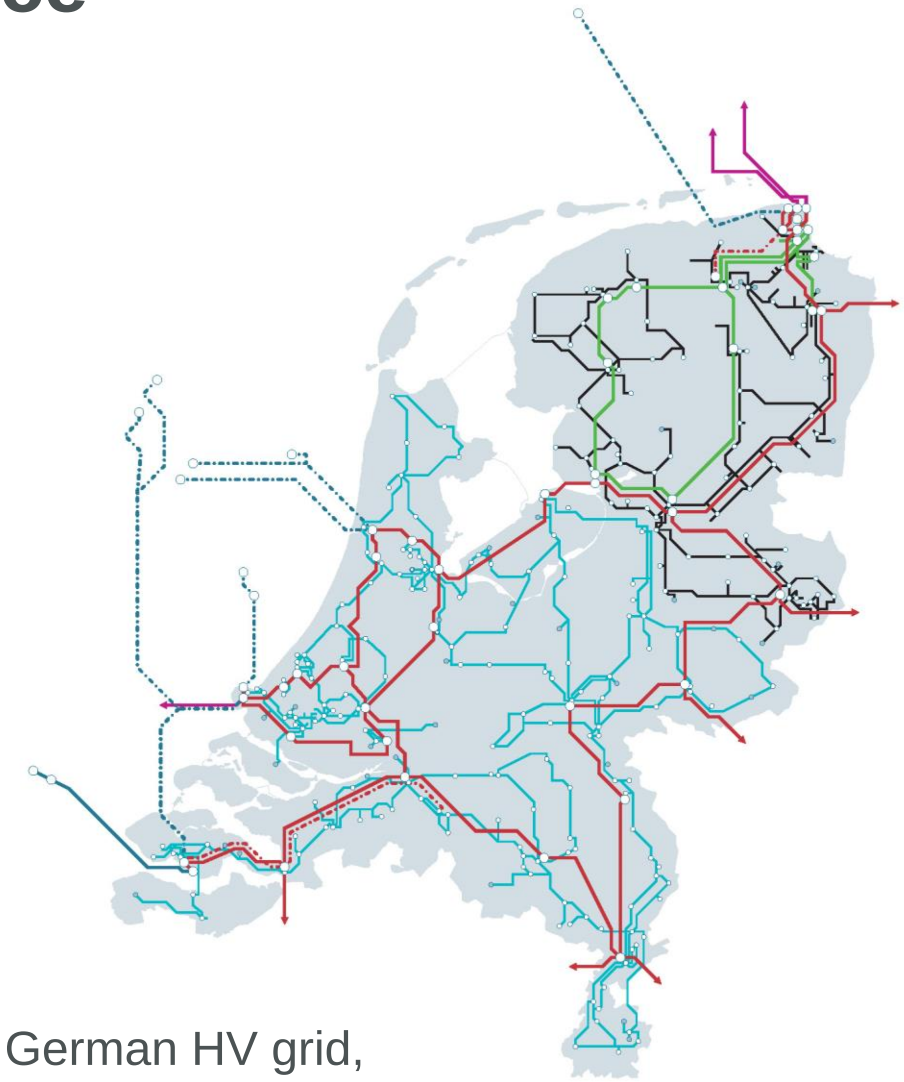
7th of February 2024, Power System Protection Centre

TU Delft TenneT

TenneT Netherlands at a glance

- Facts & figures (mostly end-2022 data)
  - Employees
    3,500+
  - Total grid length
    11,130+ km
  - Transformer substations
    342+
  - Number of end-users
    ~18 million
  - Grid availability (2023):
    99.99963%

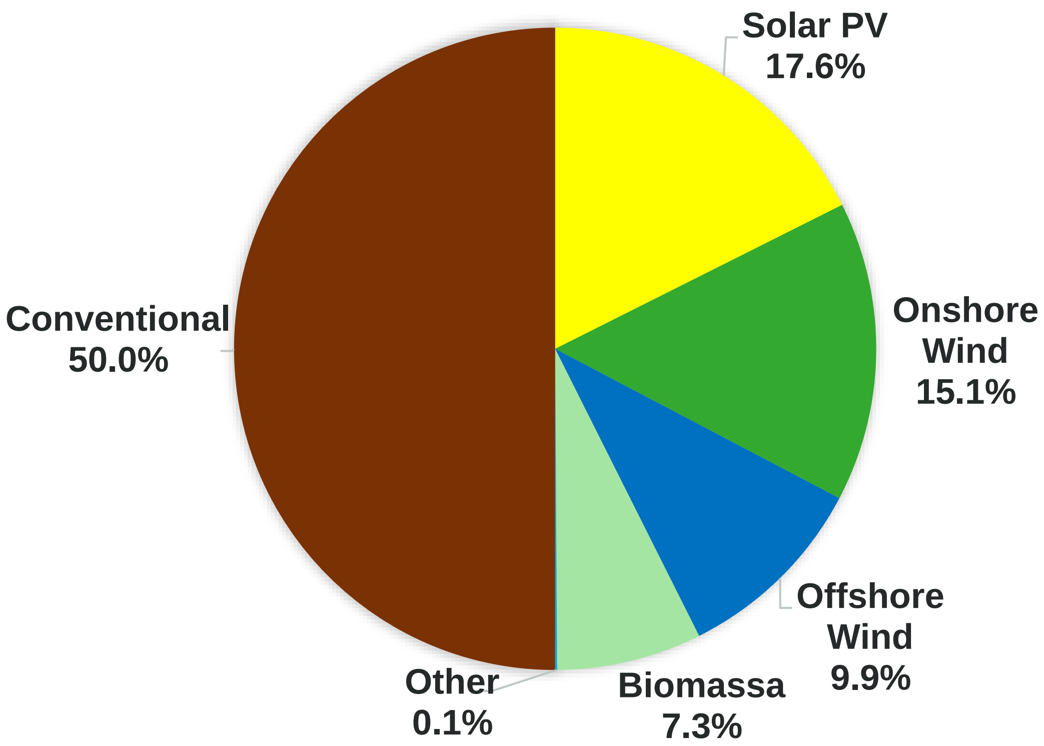


Note: TenneT also owns and operates a part of the German HV grid, but today I will focus on the Dutch transmission grid

Energy Transition in the Netherlands

- Sometimes we hear that the energy transition is not going fast enough;
  - The electrical power systems are, however, changing incredibly fast!
- Half of electricity in the Netherlands (2023) was renewable. We aim for 70% by 2030 (Klimaatakkoord)
- Many hours of grid operation are already >> 50% renewable (we even had ~100% several times!)
- The other 50% will be *much harder* to achieve, mainly due to *grid* bottlenecks (congestions, system strength & inertia, stability limits, P & Q reserves…)

ELECTRICITY PRODUCTION NL 2023
~HALF WAS RENEWABLE



Source: Energieopwek.nl

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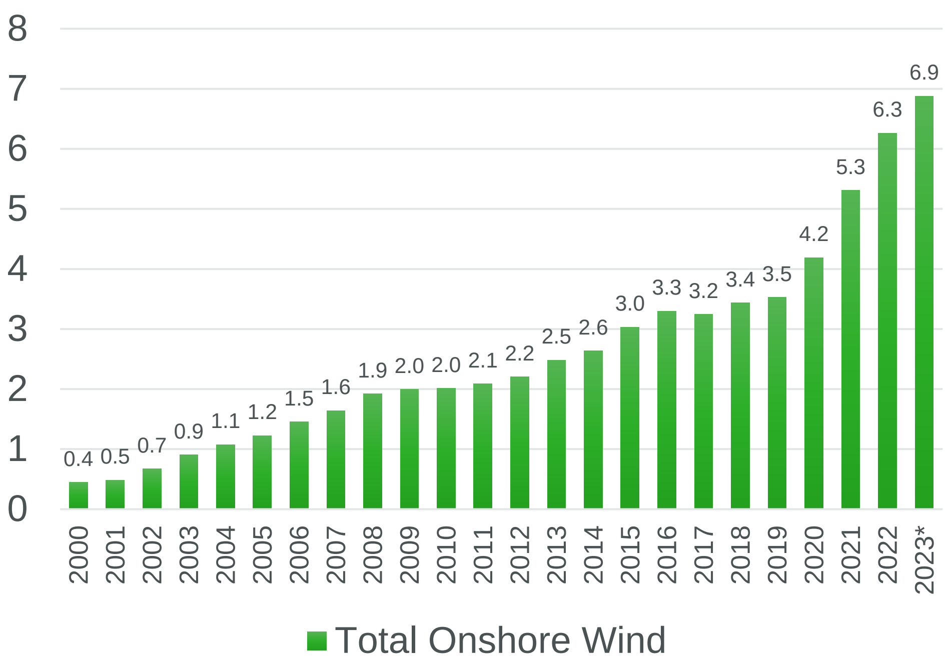
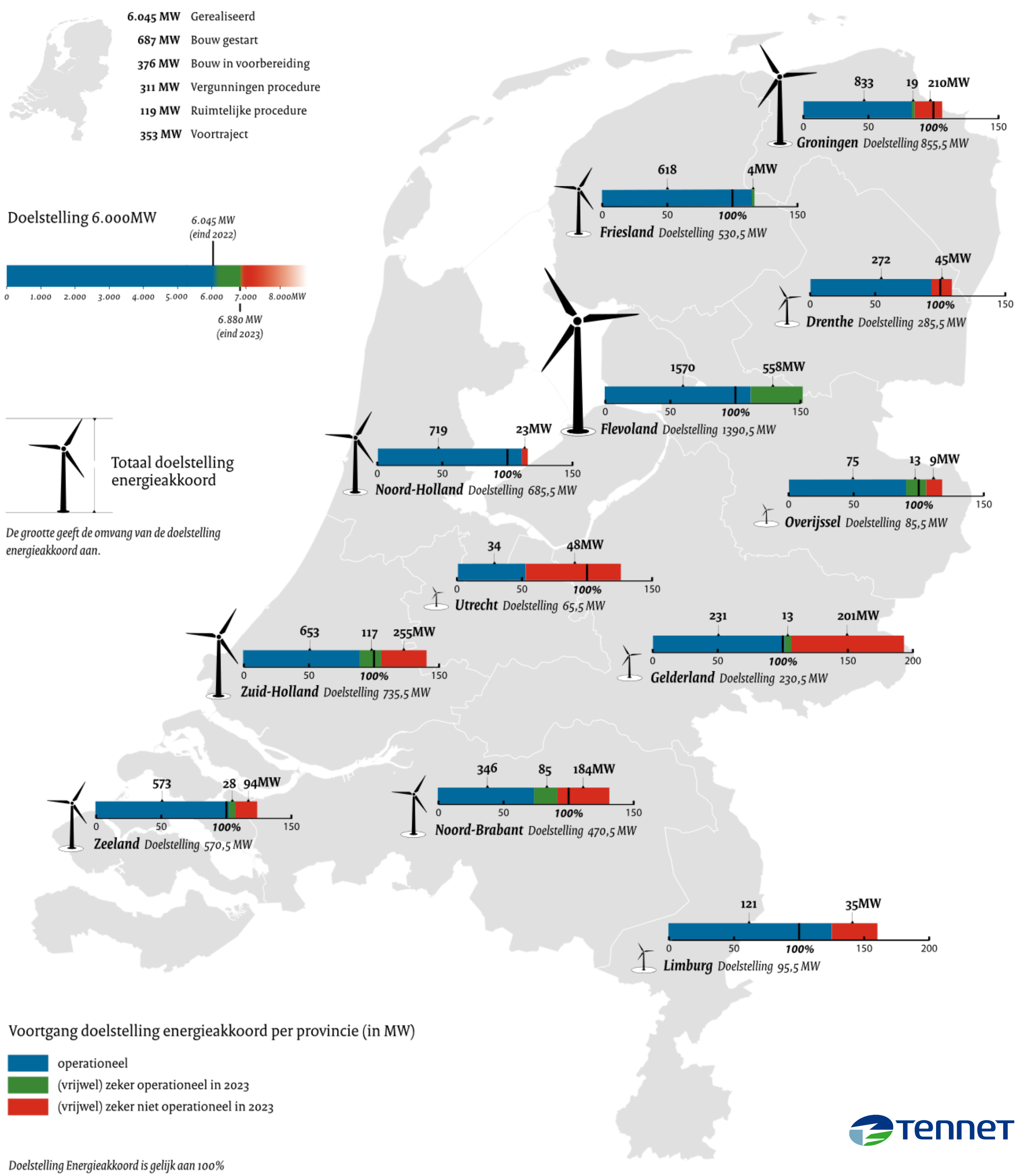
Onshore Wind trends

The Netherlands

- Installed power is **very high and growing**, particularly in provinces closer to the coast

Onshore Wind installed capacity the Netherlands [GW]





Source: CBS, RVO

6 February, 2024

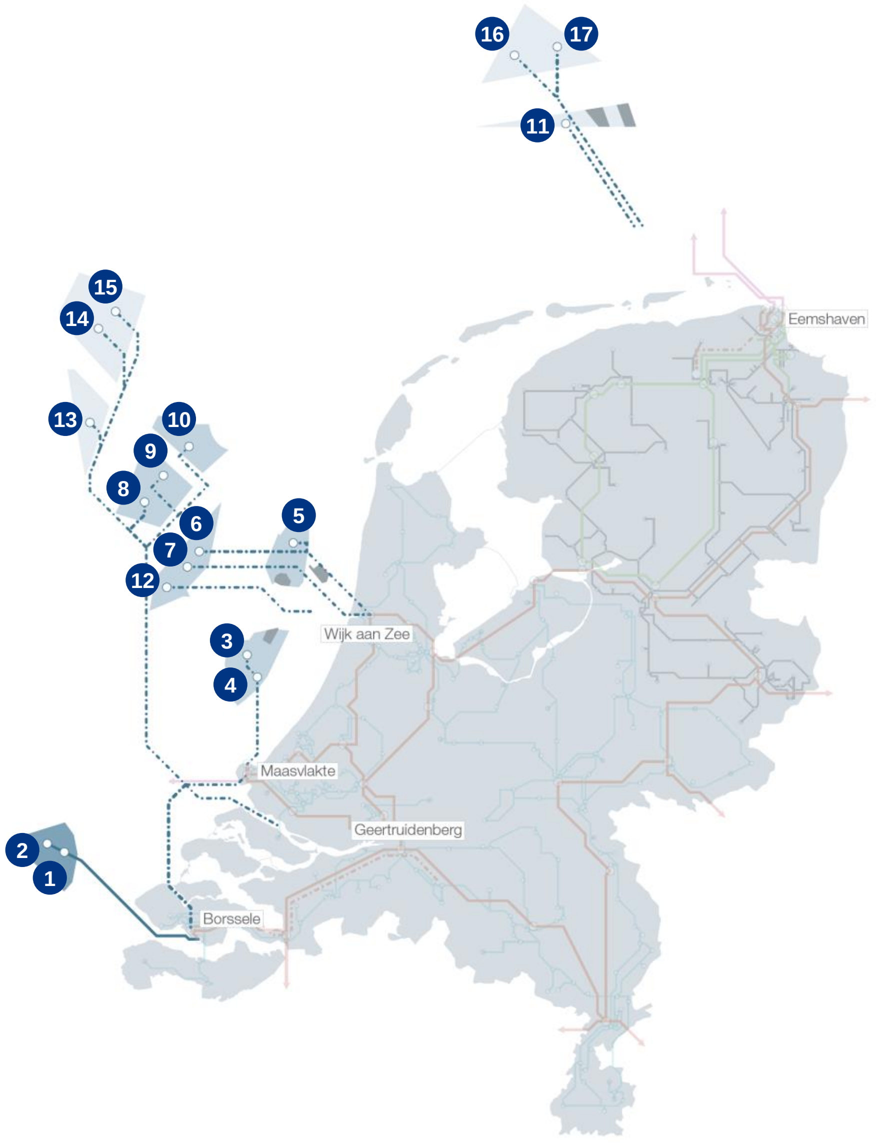
Offshore Wind trends

The Netherlands

4.7 GW end of 2023 → **~21 GW around 2030**

1	Borssele Alpha	700	MW (AC)	2019
2	Borssele Beta	700	MW (AC)	2020
3	Hollandse Kust (zuid) Alpha	700	MW (AC)	2022
4	Hollandse Kust (zuid) Beta	700	MW (AC)	2022
5	Hollandse Kust (noord)	700	MW (AC)	2023
6	Hollandse Kust (west Alpha)	700	MW (AC)	2024
7	Hollandse Kust (west Beta)	700	MW (AC)	2026
8	IJmuiden Ver Alpha	2.000	MW (DC)	2029
9	IJmuiden Ver Beta	2.000	MW (DC)	2028
10	IJmuiden Ver Gamma	2.000	MW (DC)	2029
11	Ten Noorden van de Wadden	700	MW (AC)	2031
12	Hollandse Kust (west), kavel VIII	700	MW (AC)	n.t.b.
13	Nederwiek 1	2.000	MW (DC)	2030
14	Nederwiek 2	2.000	MW (DC)	2030
15	Nederwiek 3	2.000	MW (DC)	~2031
16	Doordewind 1	2.000	MW (DC)	~2031
17	Doordewind 2	2.000	MW (DC)	~2031

AC to DC



- Large shift from AC to DC Offshore Wind integration, starting with Ijmuiden Ver Alpha & Beta in ~2029

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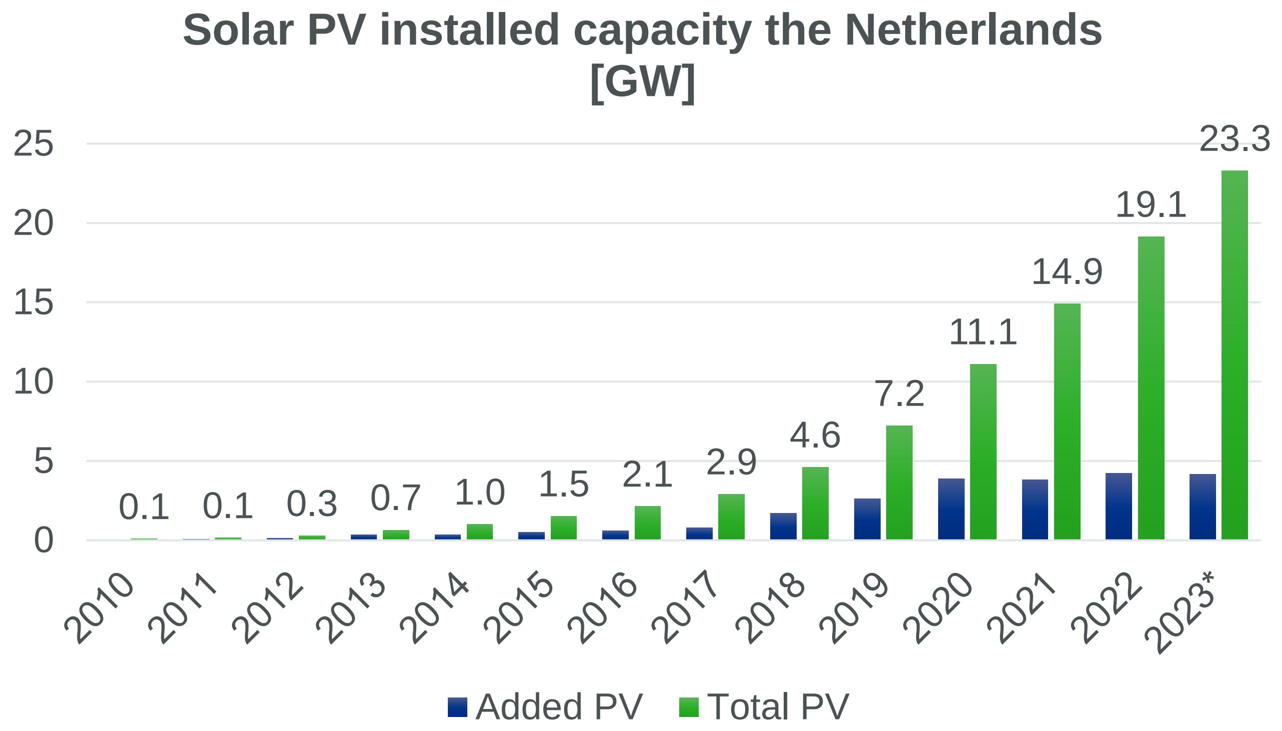
Solar PV trends

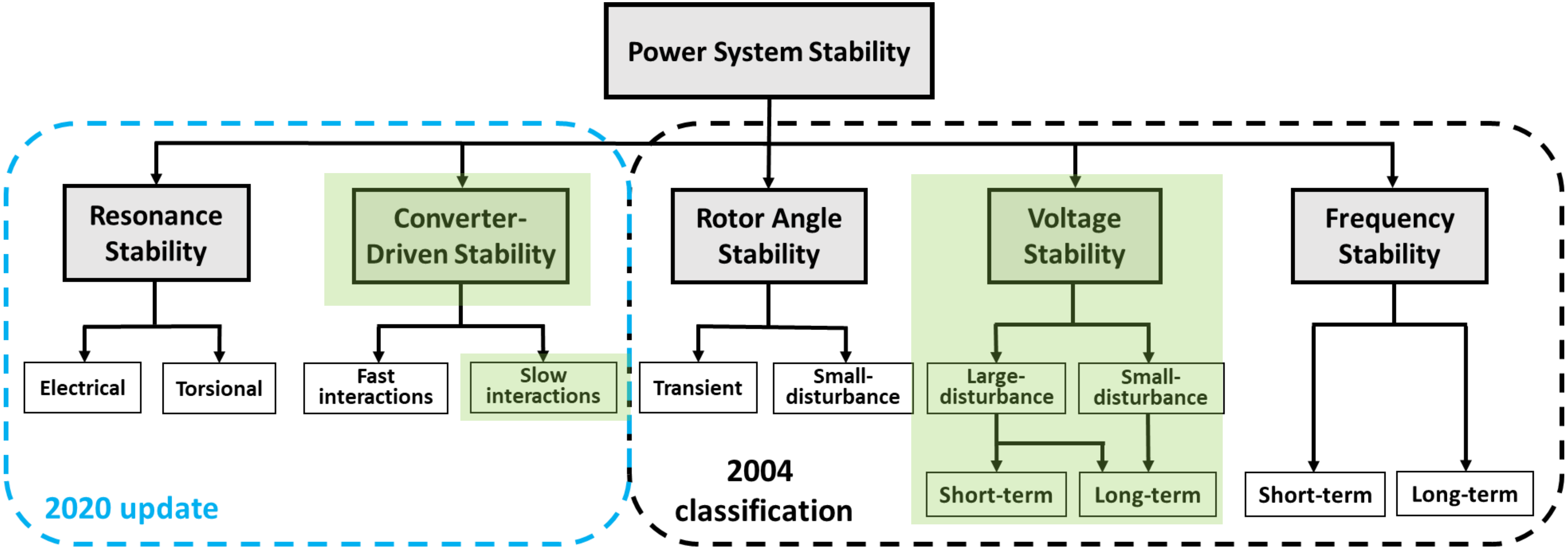
The Netherlands

- Besides the large wind power capacity – the Netherlands is the global leader in installed Solar PV capacity per capita (we surpassed Australia in 2023!)
- ~18 million people, the average of ~1.3 kW of installed PV per person (~4 typical PV panels)



Source: CBS

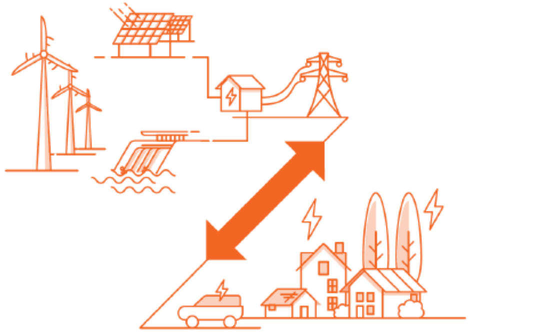
Stability in Evolving Power Systems



Green: Focus of this presentation

Where does **system strength** fit here?

More asynchronous generation

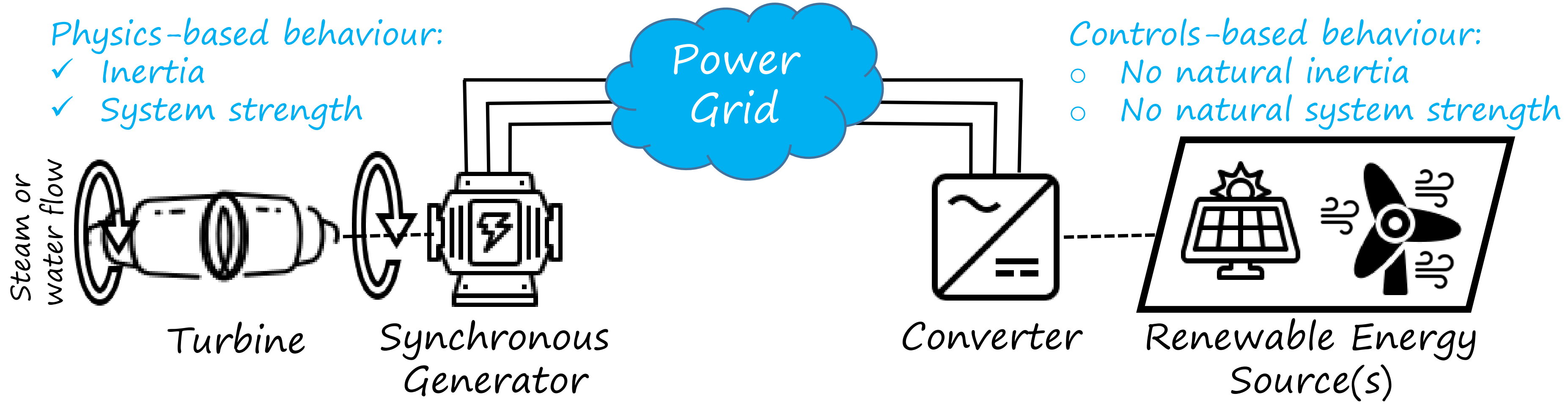


Generation moving to different areas

Sources:
- N. Hatziargyriou et al., "Definition and Classification of Power System Stability – Revisited & Extended," in IEEE Transactions on Power Systems, 2020
- A. Boričić, PhD Thesis, TU Delft (April 2024)

The effects on system stability and resilience

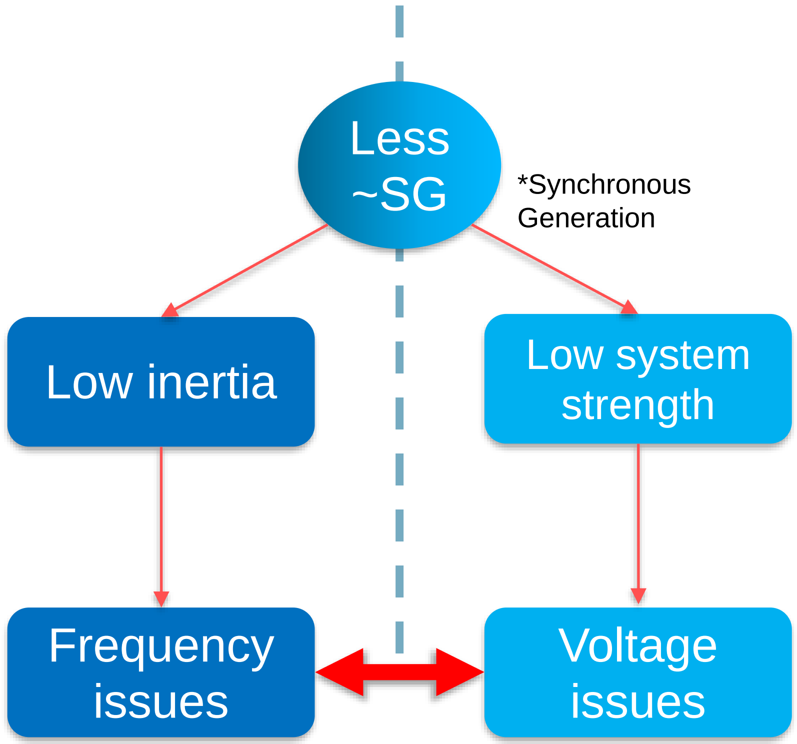
- More and more inverter-based resources (IBRs), relative to synchronous generation (SG)



- The result is a fundamental decrease in system strength and inertia. Both used to be abundant, as free "by-products" of synchronous generators
- The vast majority of IBRs do not provide either. Furthermore, IBRs also *require* sufficient strength
- Two simultaneous effects: The grid *and* generation both become more sensitive & less resilient

Sources:
- A. Boričić, PhD Thesis, TU Delft (April 2024)

System Strength Fundamentals



System strength is to voltage what inertia is to frequency!

INERTIA (Frequency Resilience)

- Newton's & Euler's Laws
- Stored kinetic energy (rotation)
- Opposes changes in rotational speed (frequency)

SYSTEM STRENGTH (Voltage Resilience)

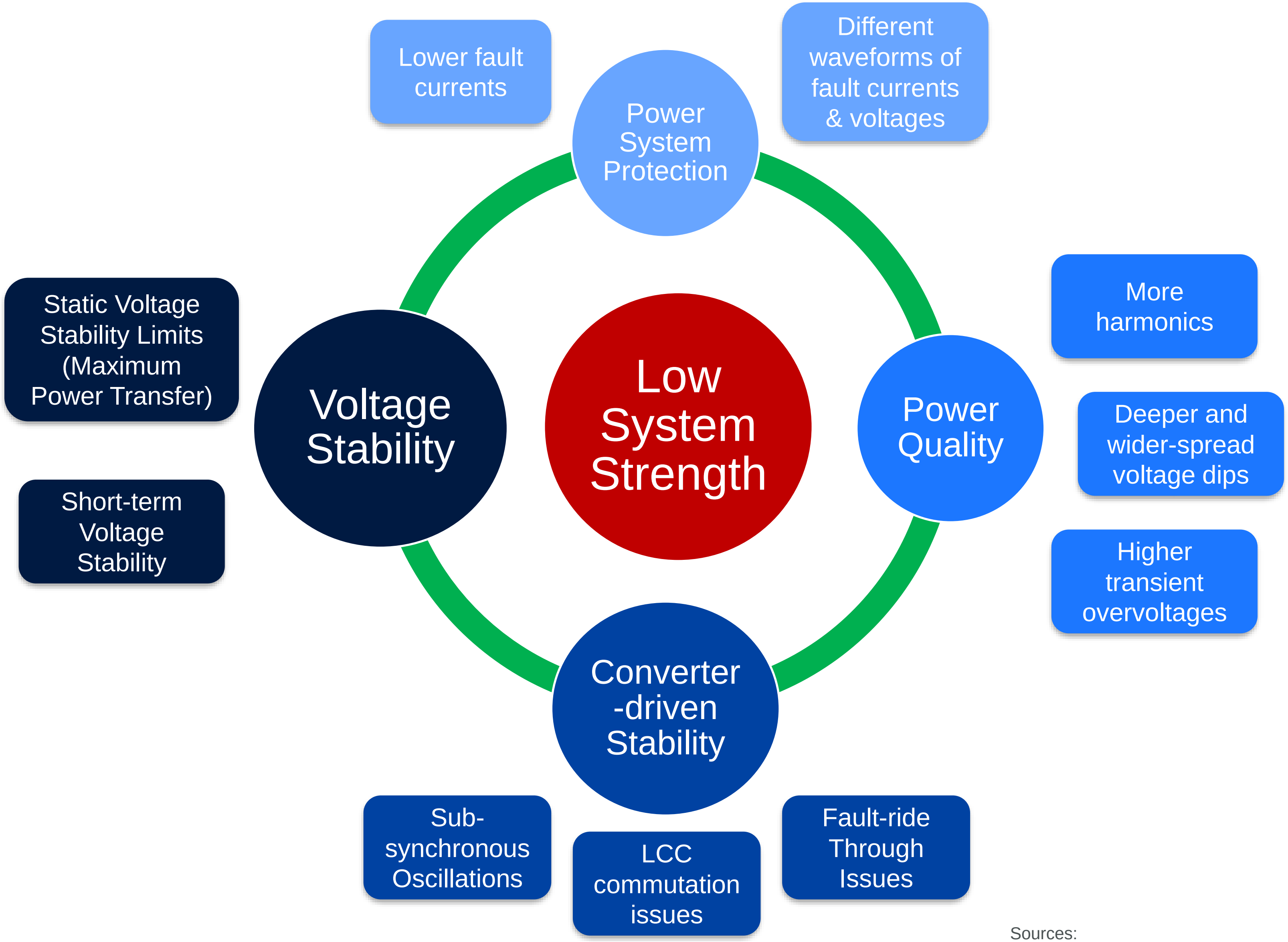
- Faraday's & Lenz' Law
- Strong magnetic coupling (flux)
- Opposes changes in EMF (voltage)

DEFINITION:

***System strength** refers to the ability of a power system to maintain stable voltages in both steady- and dynamic-state and to avoid related instabilities and cascading. Symptoms of low system strength include reduced voltage stability limits and maximum power transfer, higher voltage sensitivity, as well as elevated susceptibility to converter-driven interactions, oscillations, desynchronization, and instabilities.*

Sources:
- A. Boričić, PhD Thesis, TU Delft (April 2024)

Major Consequences of Low System Strength



Sources:
- A. Boričić, PhD Thesis, TU Delft (April 2024)

Static Voltage Stability Limits
Maximum Power Transfer

- Every transmission corridor has two limits:
  - Thermal limits of the line/cable (incl. sag limits)
  - Static voltage stability limits (also known as system limits)

  Systems must be operated below both to ensure static grid security!

- System limits *differ* depending on a power source (Synchronous vs IBR). IBR-rich grids have lower limits due to their weak electromagnetic link with the grid ("decoupled" operation, not a "true" voltage source)

- Thermal limits used to be higher than system limits, hence it was rarely necessary to comprehensively analyze system limits
  - In evolving power systems, this is rapidly changing. Some TSOs already curtail renewable generation due to operational *static voltage stability limits;* e.g. Ireland, UK, Texas, Australia... (even though the thermal limits are not reached)

- Therefore, lower system strength reduces the maximum power transfer over the respective transmission corridor

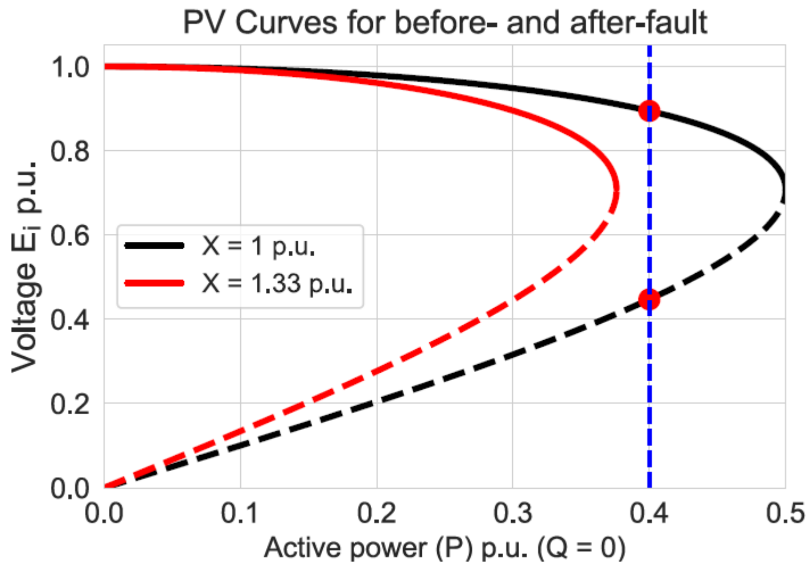


Figure 2.9.: Example of PV curves before and after a fault.

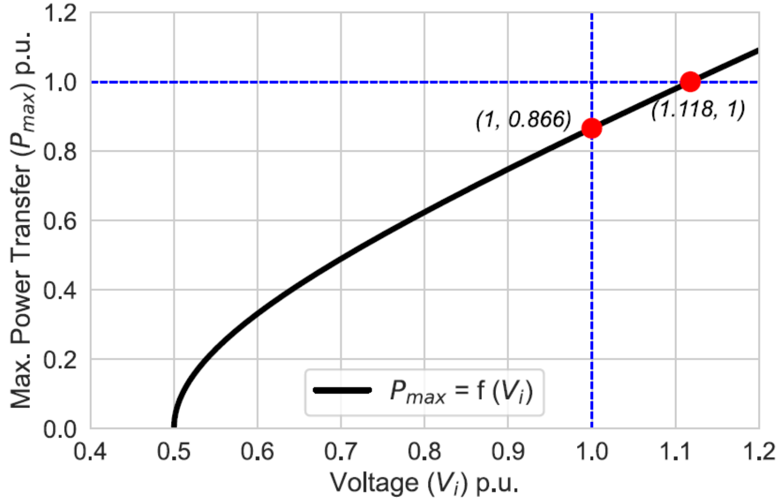


Figure 3.7.: Maximum power transfer as a function of operating voltage.

Sources:
- A. Boričić, PhD Thesis, TU Delft (April 2024)

Short-term Voltage Stability

- Complex phenomenon, typically involving several of the following aspects:
  - Pre-fault weak-grid operation (e.g. high power transfers, high share of IBRs, low strength…)
  - Large disturbance triggering the cascade
  - Failure of units to ride-through and/or support the grid (e.g. IBRs, HVDCs…)
  - Demand drawing high Q during a voltage drop (e.g. motors, inverter-based const-P loads...)
    - **Possible consequence: Voltage collapse**
- Typically occurs very fast (few seconds), leaving the operators unable to respond
- “Trouble likes company”
  - STVS is often intertwined with other fast phenomena (oscillations, rotor angle instability, cascading, network separations, frequency collapse…).

Australia Blackout 2016

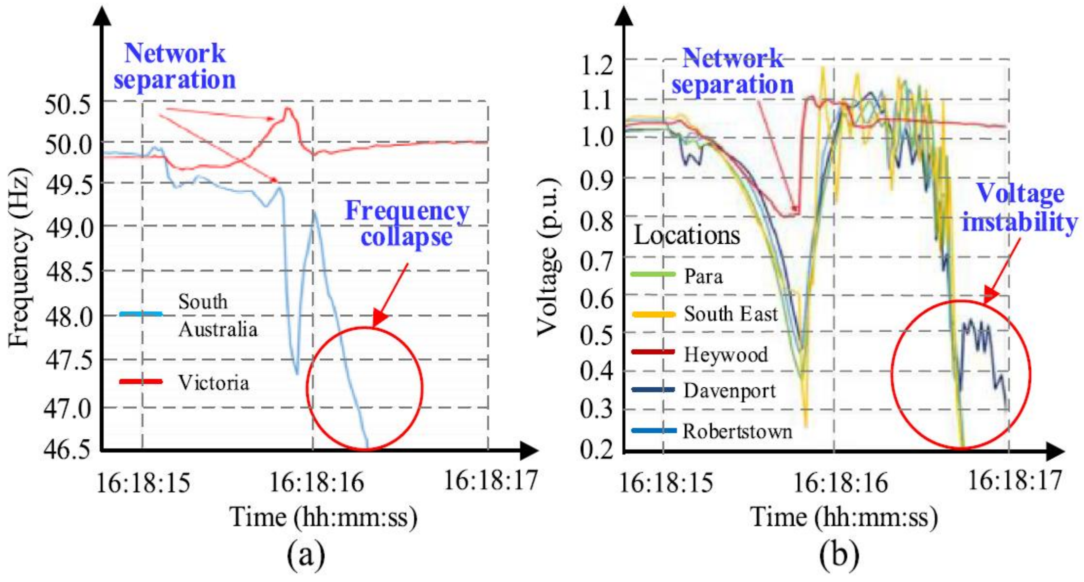
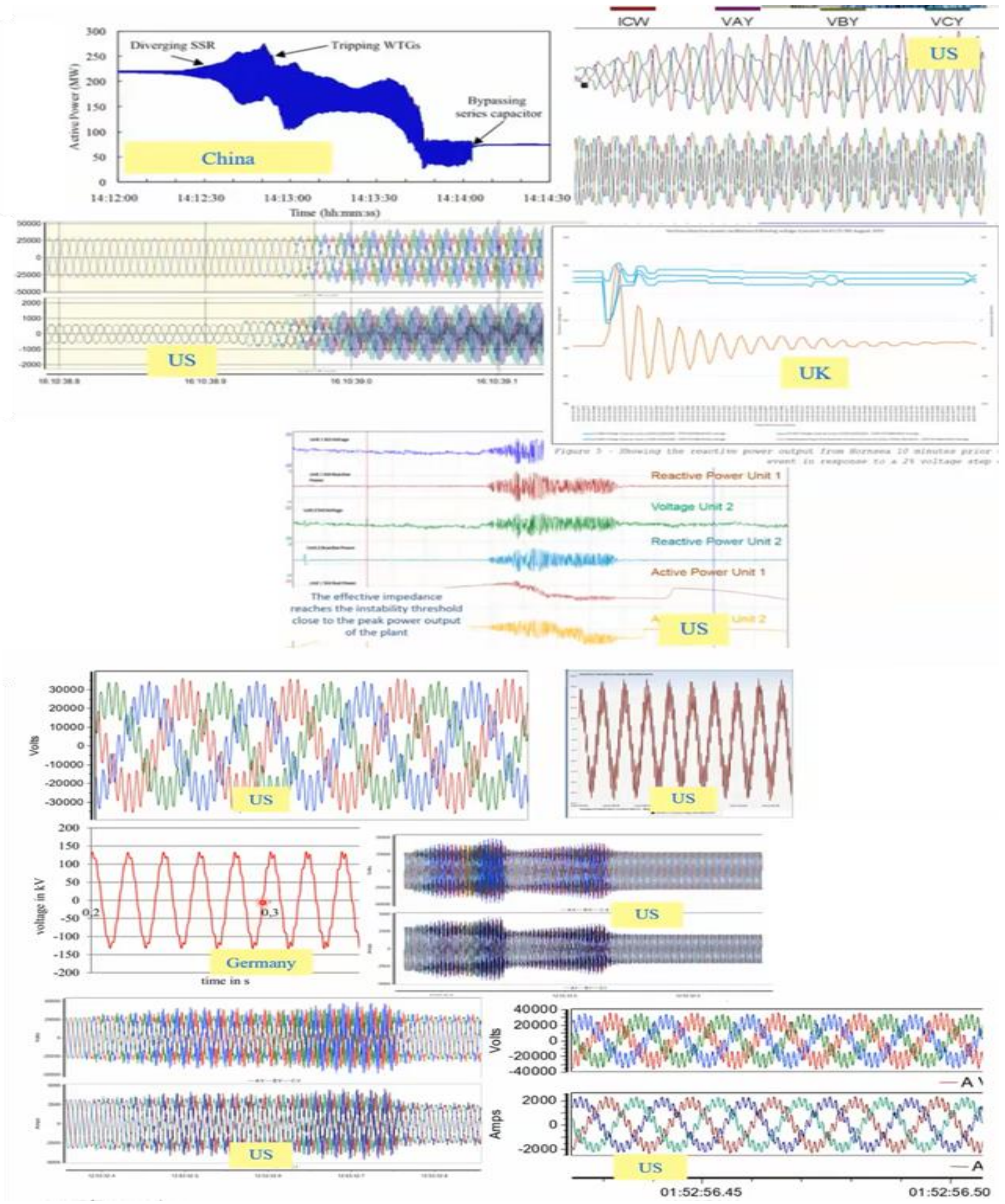


Fig. 2. 2016 South Australian blackout. (a) Frequency collapse; (b) Voltage instability [12].

Sources:
- R. Yan, et al. "The Anatomy of the 2016 South Australia Blackout: A Catastrophic Event in a High Renewable Network," in IEEE Transactions on Power Systems, 2018
- A. Boričić, PhD Thesis, TU Delft (April 2024)

Converter-driven Stability
Sub-synchronous Oscillations

- Weak grids naturally experience higher voltage sensitivity (high impact of current injections due to high impedance)
- Meanwhile, most IBRs require stable voltage waveforms to operate (e.g. due to PLL, but also inner & outer control loops)
- The result: sensitive equipment follows a sensitive system – the recipe for interactions and oscillations
- Many oscillations were reported worldwide, incl. Europe
- These weak-grid oscillations are typically in the 5 – 15 Hz range, but may also exhibit other frequencies
  - If unresolved, they often lead to IBR(s) tripping, which may initiate further cascading



Sources:
- ESIG, NREL
- Y. Cheng et al., "Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," in IEEE Transactions on Power Systems, 2023
- A. Boričić, PhD Thesis, TU Delft (April 2024)

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Converter-driven Stability
Fault-ride Through Issues

- Modern grid codes require IBRs to ride-through faults and support the grid voltage with (re)active current injections

- This is typically tested in the grid connection & compliance procedure, based on grid codes

- The problems, however, still arise, due to:
  - Further reduction of grid strength since the connection
  - More IBRs eventually installed in proximity (interactions)
  - Insufficiently detailed grid code compliance testing

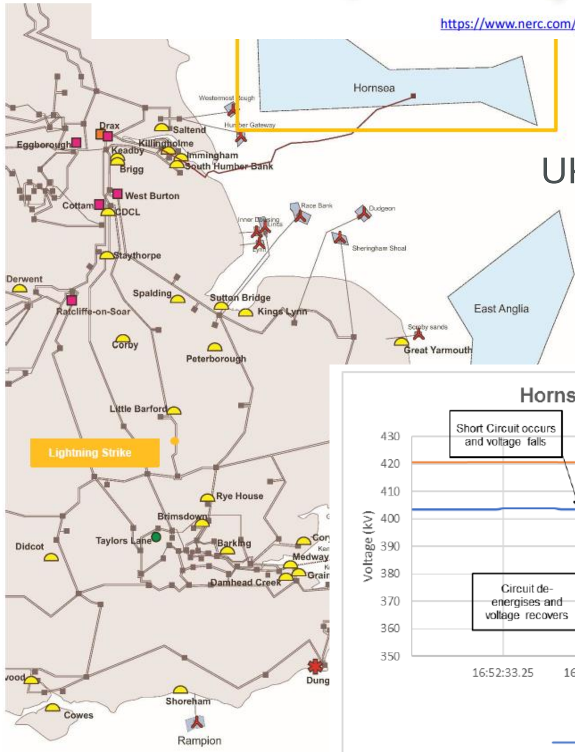
- Consequences in weak grids: More IBRs fail to ride-through faults and fail to support the grid *when it is most needed!*
  - This increases risks of cascading (e.g. UK Hornsea incident, leading to loss of supply for >1 million customers)
  - Many incidents reported worldwide

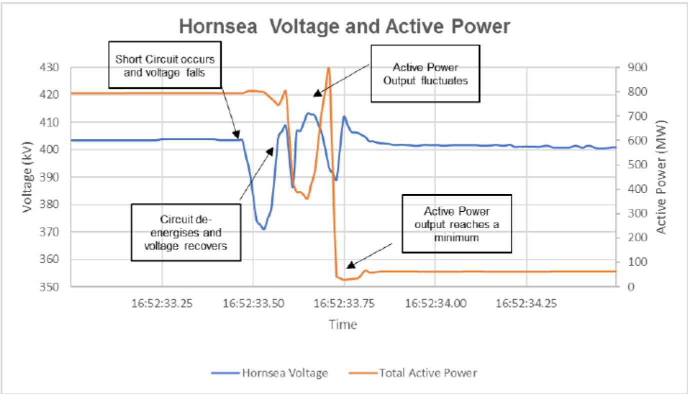
NERC Disturbance Reports and Alerts

Fault-Ride-through issues and cascading

https://www.nerc.com/pa/rrm/ea/Documents/Odessa_Disturbance_Report.pdf

UK Hornsea event (2019)

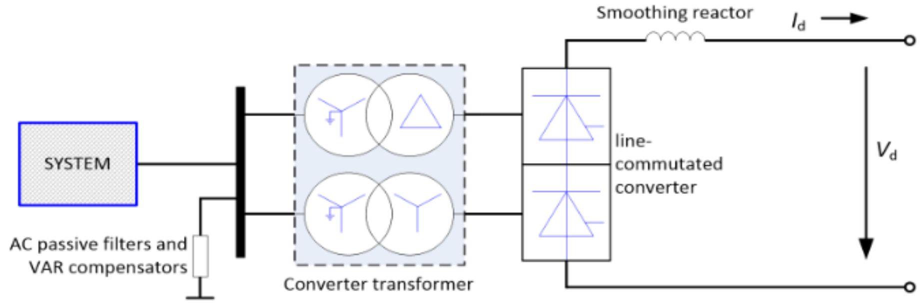


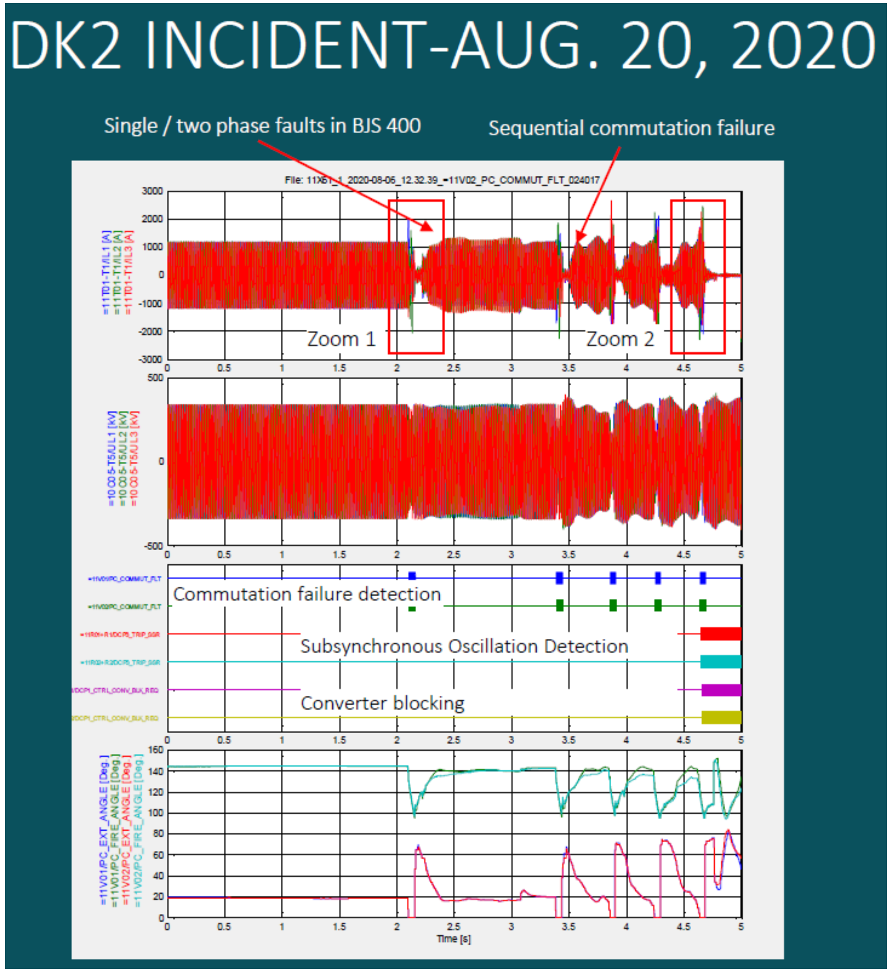


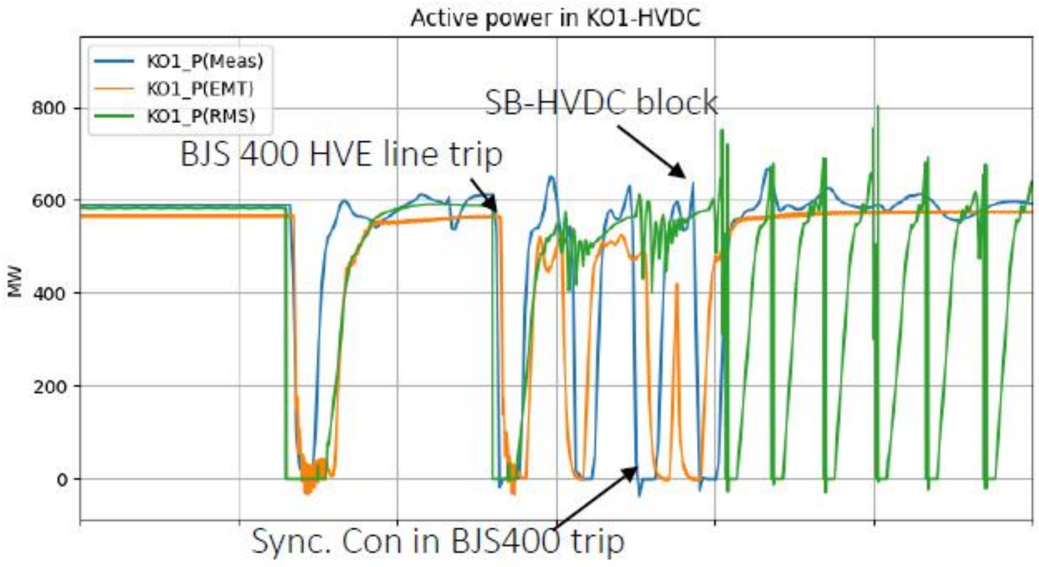
Sources:
- NERC Event Reports
- NG ESO Hornsea Incident Report

Converter-driven Stability
LCC Commutation Issues

- LCC (Line-Commutated Converter) is a technology typically applied for HVDC high-power transfers
- In the Netherlands, BritNed (NL-UK, 1000MW) and NorNed (700MW, NL-NO) are using LCC technology
- LCC behaves as a current source, and it requires strong and stable voltage to operate properly
- In weak grid conditions, commutation failures may occur (Example: Denmark, Aug 2020, courtesy of Energinet)







While the VSC technology is (advertised as) more resilient, it also has its weak-grid limits!

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Solutions? My perspective…(1/2)

What can we do to mitigate these issues? A lot, and we must do it fast…

- System Operation: More comprehensive (voltage) stability and system strength analysis
  - System stability evaluation in (real-time) operation & in the control rooms
  - Advanced system strength screening methods for weak-grid conditions and their consequences
  - Advanced monitoring, protection and control, e.g. using PMUs, WAMPAC (“meten is weten”)

- System Planning: Design a robust and future-proof system
  - Grid strengthening considering stability and strength challenges:
    - Synchronous condensers (stand-alone or combined with e.g. batteries)
    - Lower the grid impedance (more parallel lines, transformers, FACTS devices…)
    - Design markets for inertia and system strength services (we must actively provide this!)
    - Promote implementation of advanced controls that behave better in weak-grids (e.g. Grid-Forming, first for BESS (low-hanging fruits), and then for VSC HVDC links and other IBRs in the future)
    - Grid-enhancing technologies operating in Grid-Forming mode (e.g. GFM STATCOMs)

Solutions? My perspective…(2/2)

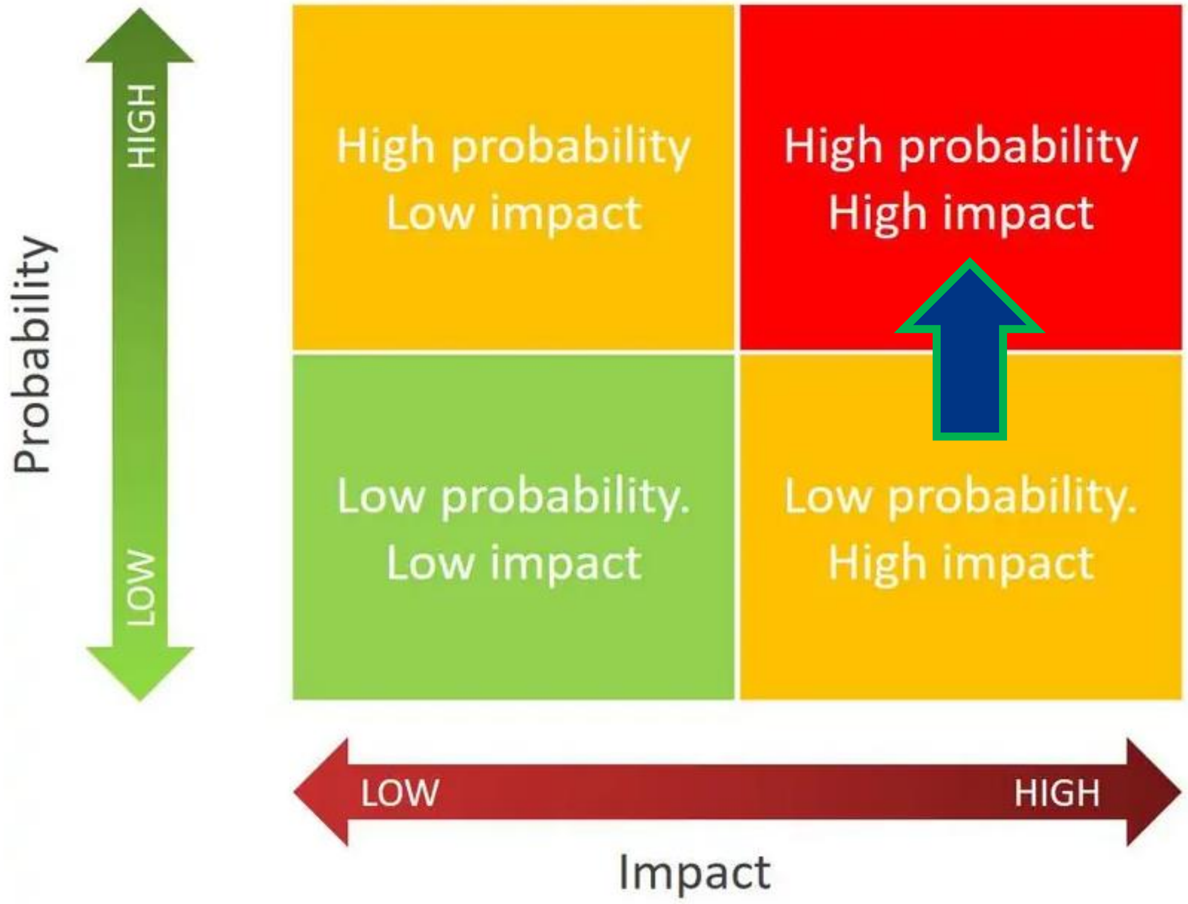
What can we do to mitigate these issues? A lot, and we must do it fast…

- Research & Innovation:
  - Better ways to evaluate grid stability and strength (faster and more accurate)
  - Metrics for fast screening of high-risk operational scenarios
  - Data-driven methods to deal with complexity and uncertainty (incl. Machine Learning, AI…)
  - Methods for selecting optimal location(s) for grid-strengthening equipment
  - Advanced IBR controls that operate stably across a wide range of grid conditions
  - Novel (system integrity) protection schemes to prevent cascading and instabilities
  - …New ideas: We cannot always solve new problems with old ideas!
- Regulations:
  - Clear functional/operational requirements for Grid-Forming converters
  - Stricter grid codes when it comes to fault-ride through and grid support
  - Demand should also contribute (rather than harm) grid stability (e.g. to define in Demand Connection Code)
  - Grant grid expansion projects a higher legal priority given their importance for energy transition

The perspective for the Netherlands

- We (will) witness a massive integration of IBRs replacing sync. generators in 2020s and 2030s
- The worldwide experience tells us that we will face many stability risks going forward
- So far, we were relatively fortunate (unaware?) regarding major dynamics in the NL due to:
  1. Still a fair amount of synchronous generation (more commonly in must-run contracts)
  2. Highly meshed grid and the ability to rely on neighboring (relatively strong, for now) grids
  3. Limited observability: SCADA ~4sec update, only a handful of PMUs operational so far
     - (We may be already experiencing initial effects, but fail to observe them)

  All of the above is going to change rapidly in the coming years!
- Developments take time – we need to act fast!



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Lighting the way ahead together

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Thank you for your attention!