Power system stability in the age of renewable energy

Annex 2 - Background on power system stability: the basics

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Distinguishing between reliability, security and stability in power systems

Reliability

Refers to the proba-bility of satisfactory operation over the long run. It denotes the ability to supply adequate electric service on an almost continuous basis.

Security

Refers to the degree of risk in the ability of the system to survive distur-bances without interruption of customer service, taking into account probabilities and consequences of contingencies.

Stability

Refers to the contin-uance of functional operation following a disturbance and the ability to return to a steady state.
It depends on the operating conditions and the nature of the disturbance.

- → While reliability and security are important for overall system performance, the emphasis here is on power system stability – ensuring the grid can withstand disturbances and return to normal operation, especially in systems with high shares of renewable energy and inverter-based technologies.
- → When reliability, security and stability criteria are not met, system splits can occur. System splits can lead to blackouts.
- → Because the massive roll-out of renewables will have a considerable impact on power system stability, innovative measures are required to ensure the stability of the future power system.

Most important power system stability phenomena

Frequency, rotor angle, voltage and resonance stability (IEEE/CIGRE 2004)*

Frequency stability ←	- Active power balance - Inertia and frequency control	Global, system-wide
Rotor angle stability ←	- Synchronising power and damping - Large power transfers	Local, regional, system-wide (depending on grid structure)
Voltage stability ←	- Reactive power balance - Large power transfers	Local, regional (depending on grid structure)
Resonance stability ←	- Controller response - Multi-frequency network characteristics	Local

→ **Frequency stability.** Ability of a power system to balance active power (generation – load) and thus to maintain frequency.

→ **Rotor angle stability.** Ability of the synchronous machines in an interconnected power system to remain synchronized following a disturbance.

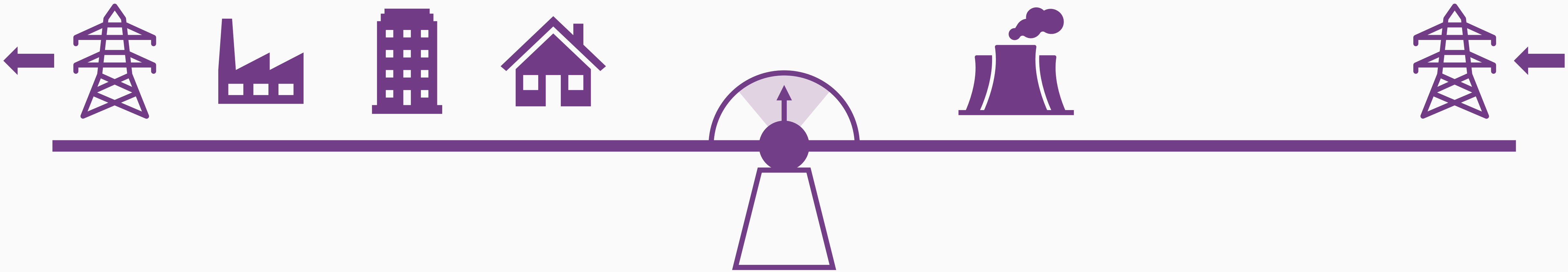
→ **Voltage stability.** Ability of a system to maintain a steady state voltage at all busbars following a disturbance.

→ **Resonance stability.** Stability resulting from the correct performance of inverters.

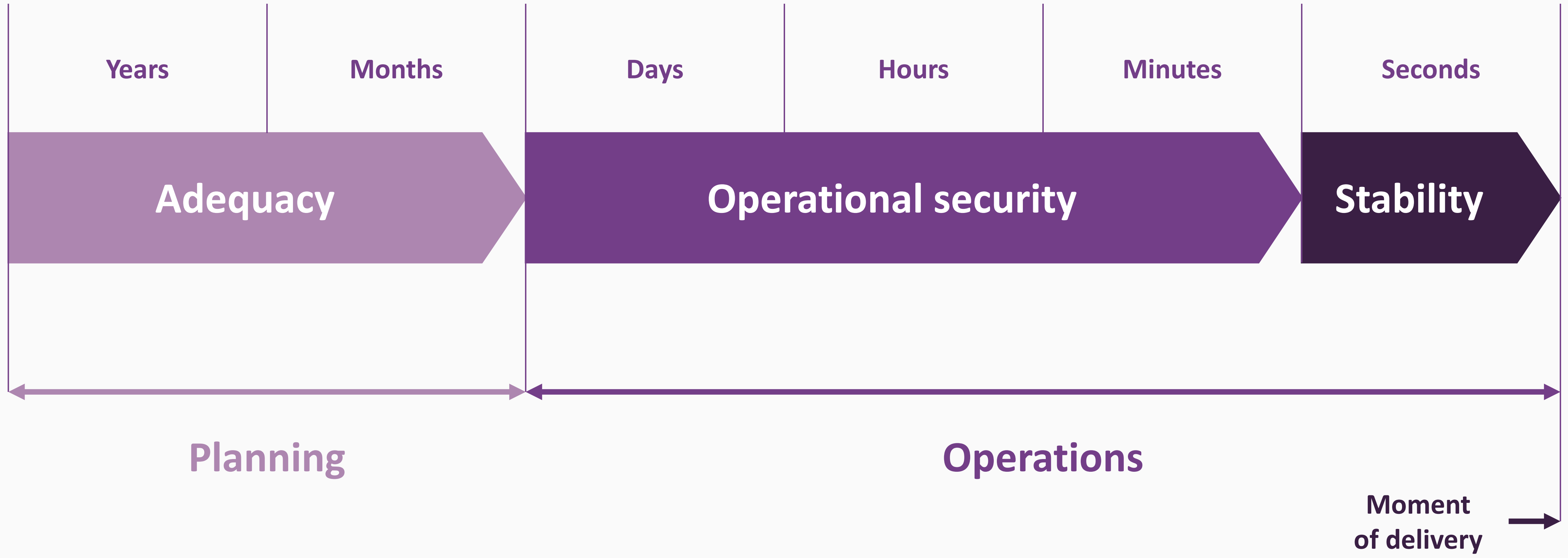
*Most important stability phenomena in power systems according to: IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, *Definition and Classification of Power System Stability, IEEE Transactions on Power Systems*, Vol. 19, No 2, May 2004.

Supply and demand must always be balanced instantaneously

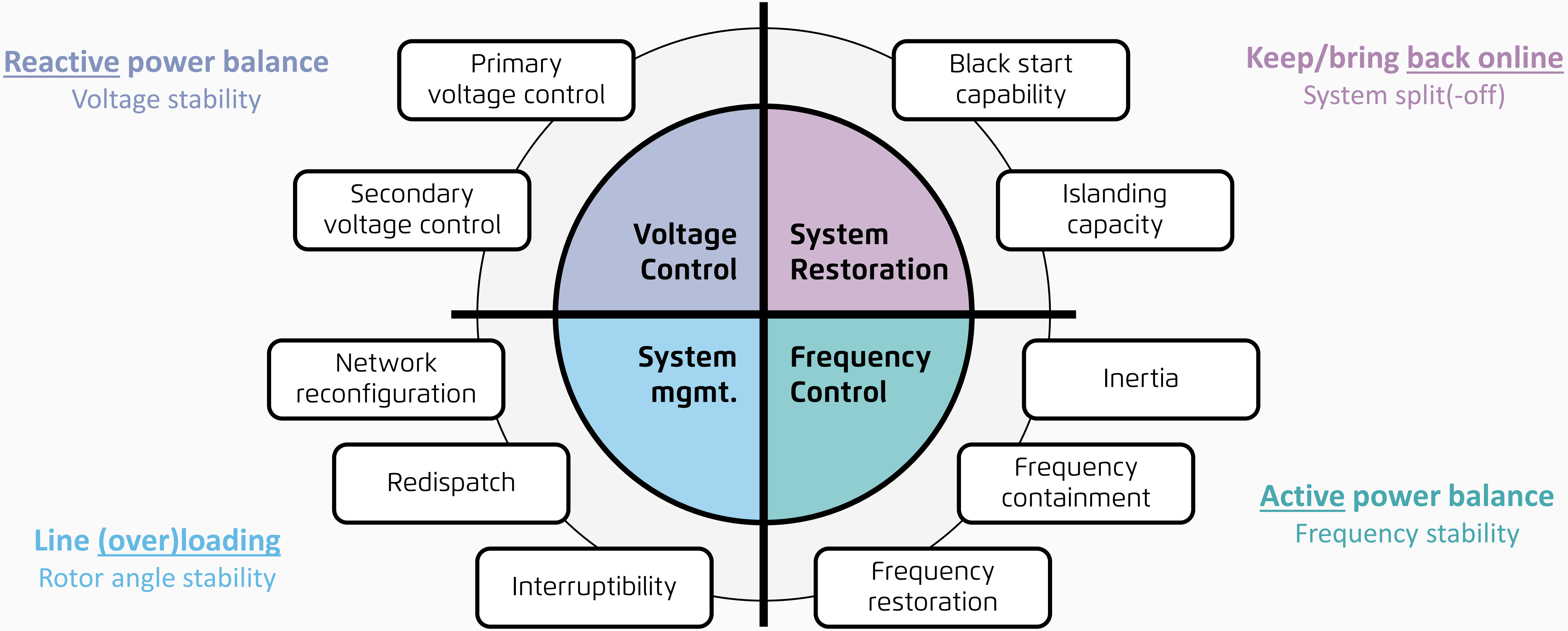
If the balance is too far off, the system crashes, leading to damaged equipment, cascading effects, and ultimately blackouts!



Maintaining system balance requires deliberate action across timescales…



.. and in different domains



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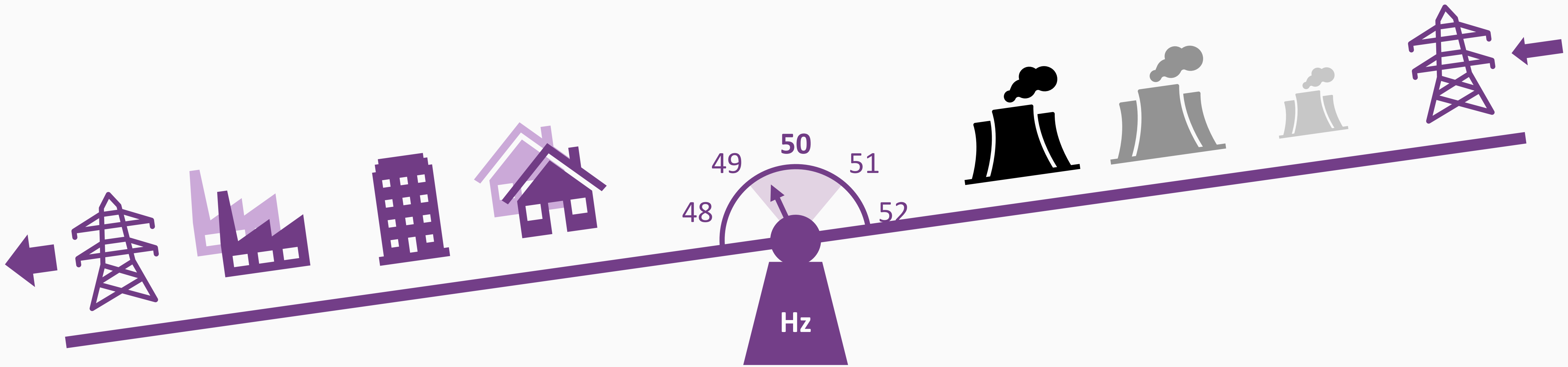
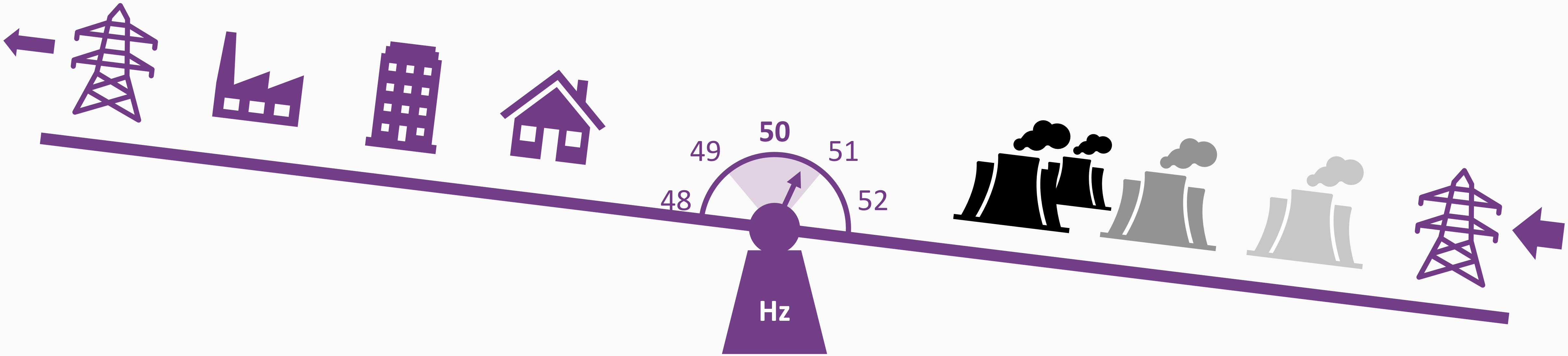
A surplus of demand will result in a decrease of frequency



While a surplus of generation will result in an increase of frequency



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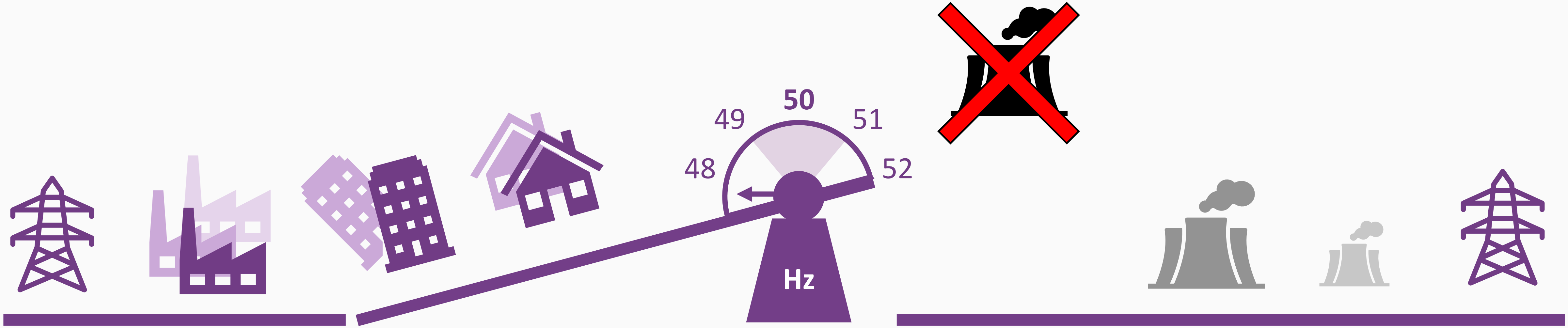
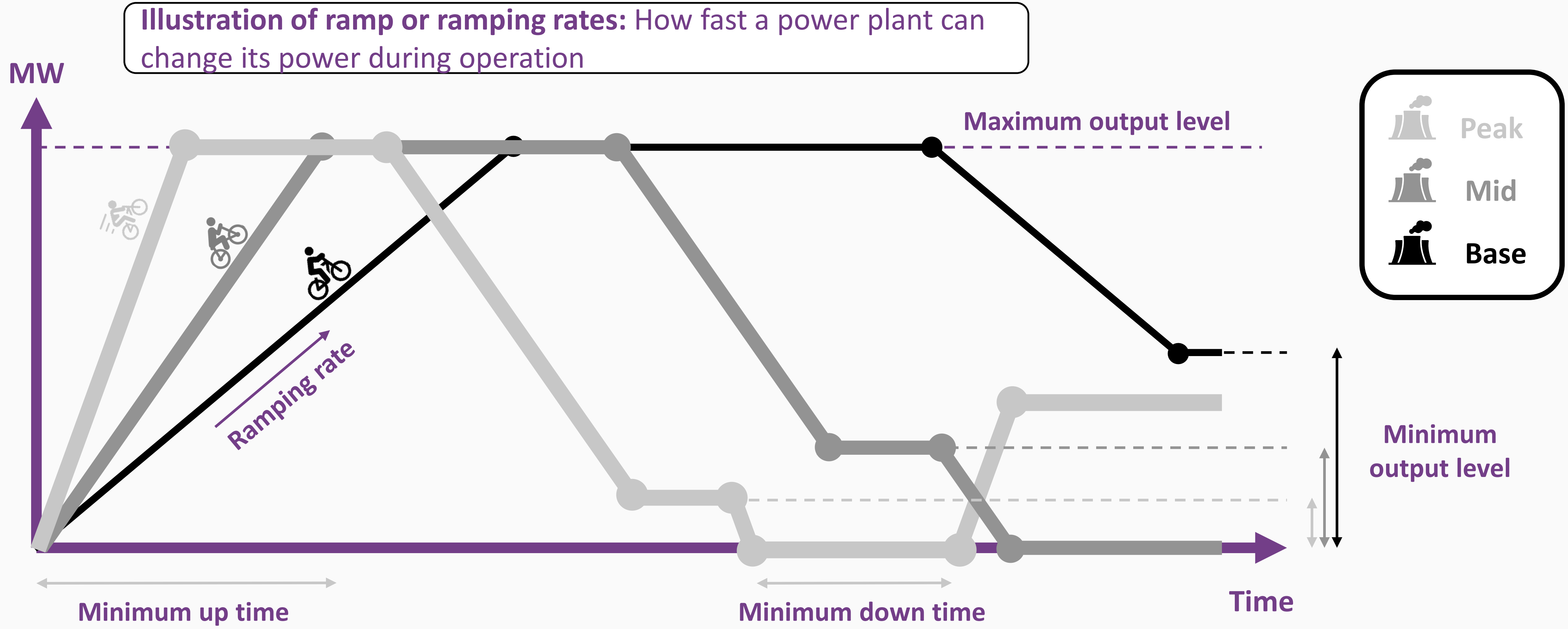
If the imbalance is too big, the system can crash

The frequency being too far outside of the safe interval is both a sign and a cause of issues
→ power plant control is crucial!

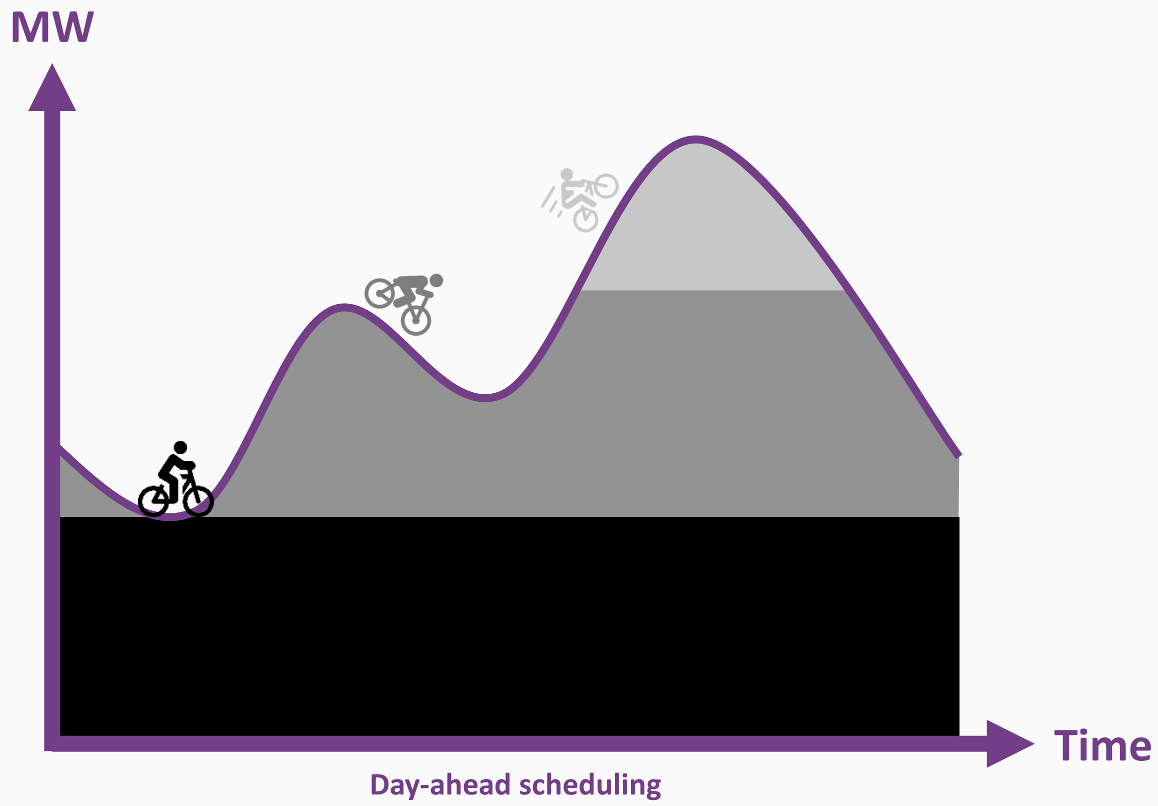


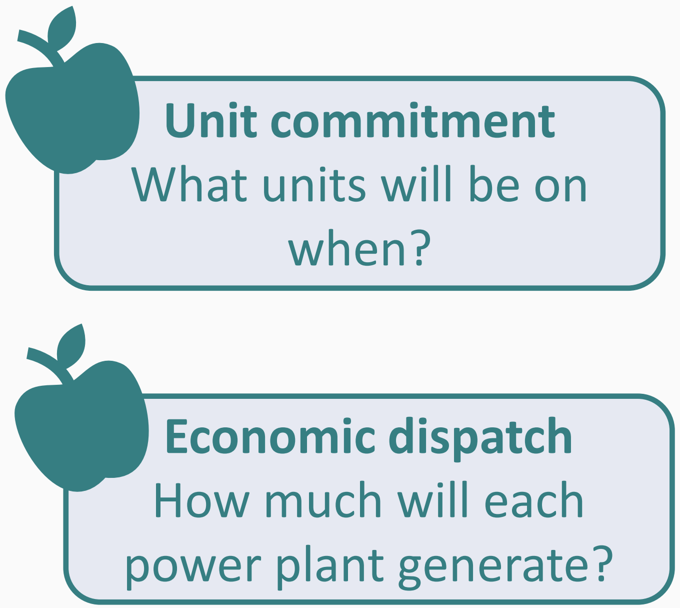
Power plants face constraints in how quickly they can adjust their output



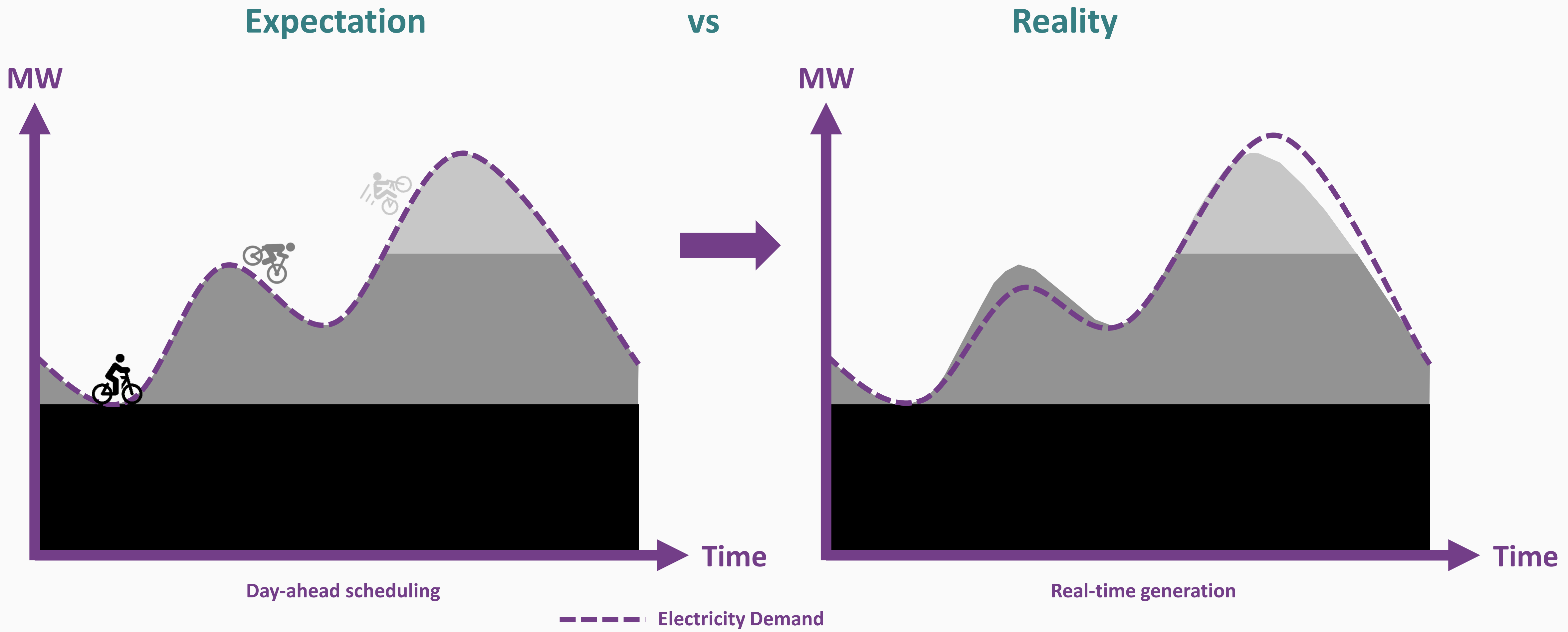
That's why system operators forecast demand and then schedule generation

For example, in Europe, scheduling decisions are made at noon for the next day (24h period starting at midnight)

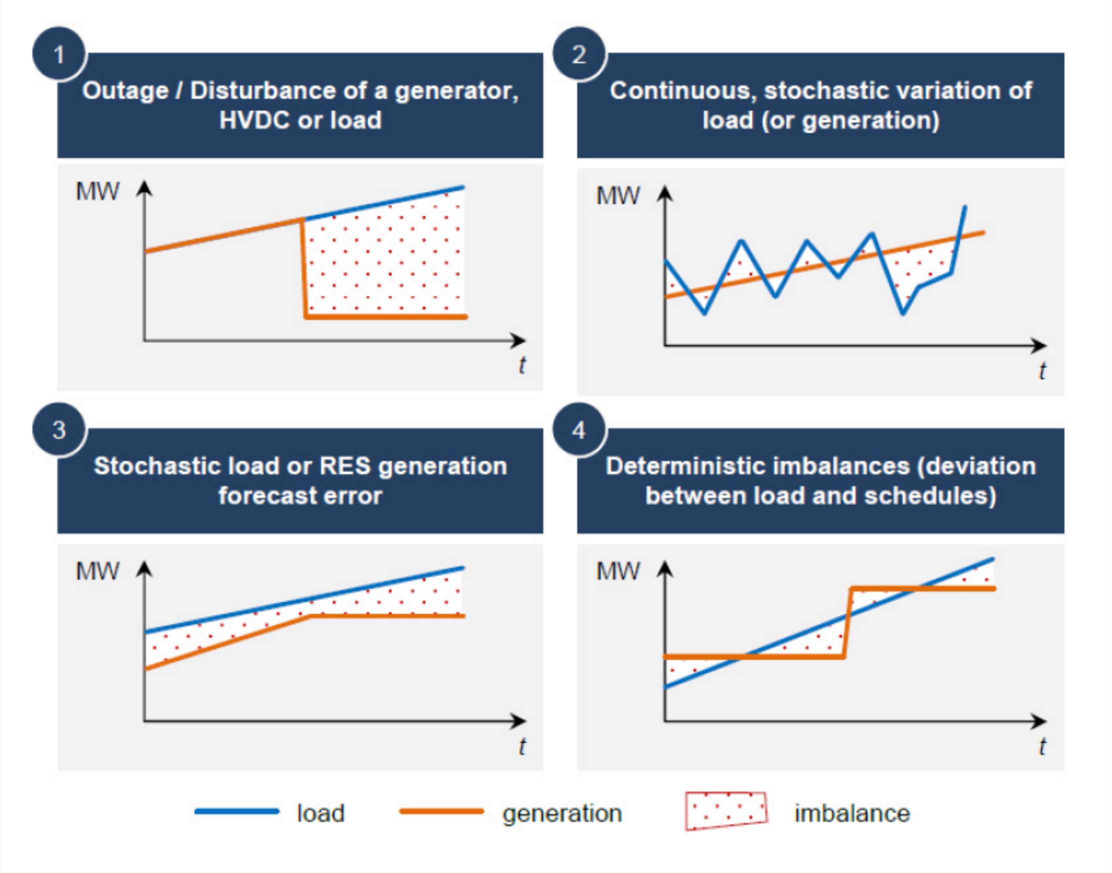




But we can't predict the future…



There are several causes for the *imbalance* between forecast and real-time



An **imbalance** is a mismatch between supply and aggregate demand

We distinguish between two groups of imbalances

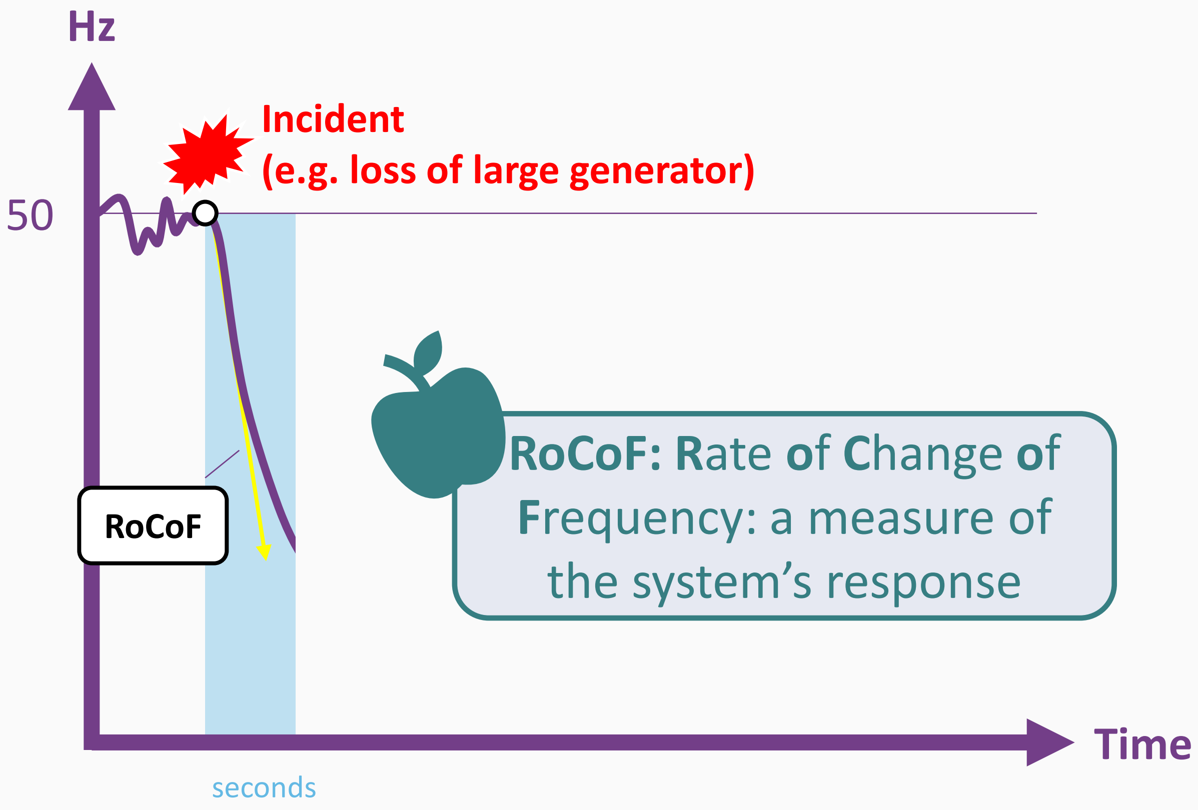
→ *Event* imbalances (e.g., outage, forecast error)

→ *Non-event* imbalances (e.g., demand variations)

The process of correcting the mismatch is called ***frequency control*** (or sometimes also *balancing*)

0-10s

Frequency control step 0: Inertia

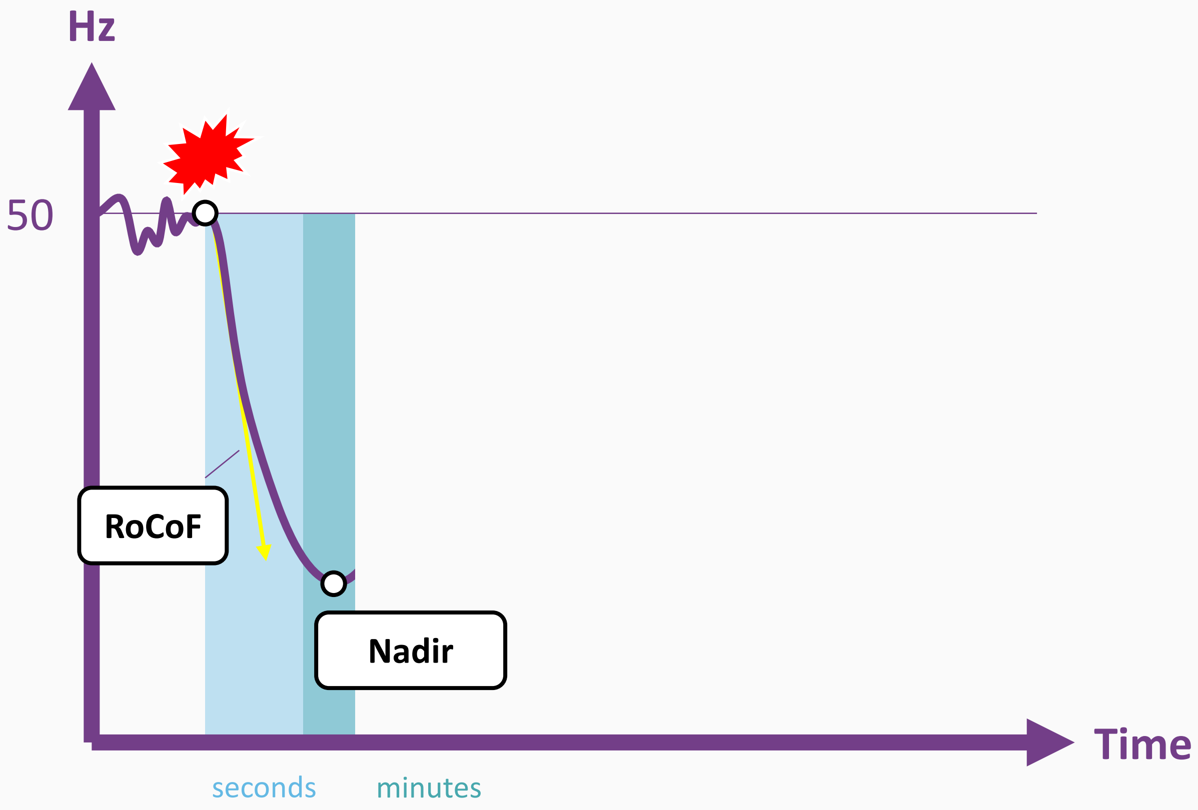


- Just like your bike doesn't stop immediately when you hit an incline, so the "spinning" mass of the generators instantaneously resists the change in frequency
- This is resistance is referred to as the system's inertia
- A system's inertia can be measured by its Rate of Change of Frequency (RoCoF)

"Synchronized"
All power plants' spinning generators are in sync

0-60s

Frequency control step 1: containment or primary response



- Certain plants, which have been equipped beforehand for this purpose, automatically adjust their output based on the frequency deviation.
- These plants often can respond quickly but cannot maintain that output for very long.
- In some systems, this is known as frequency containment reserves, as they stop (contain) the drop in frequency.
- The nadir is the lowest point of a curve.

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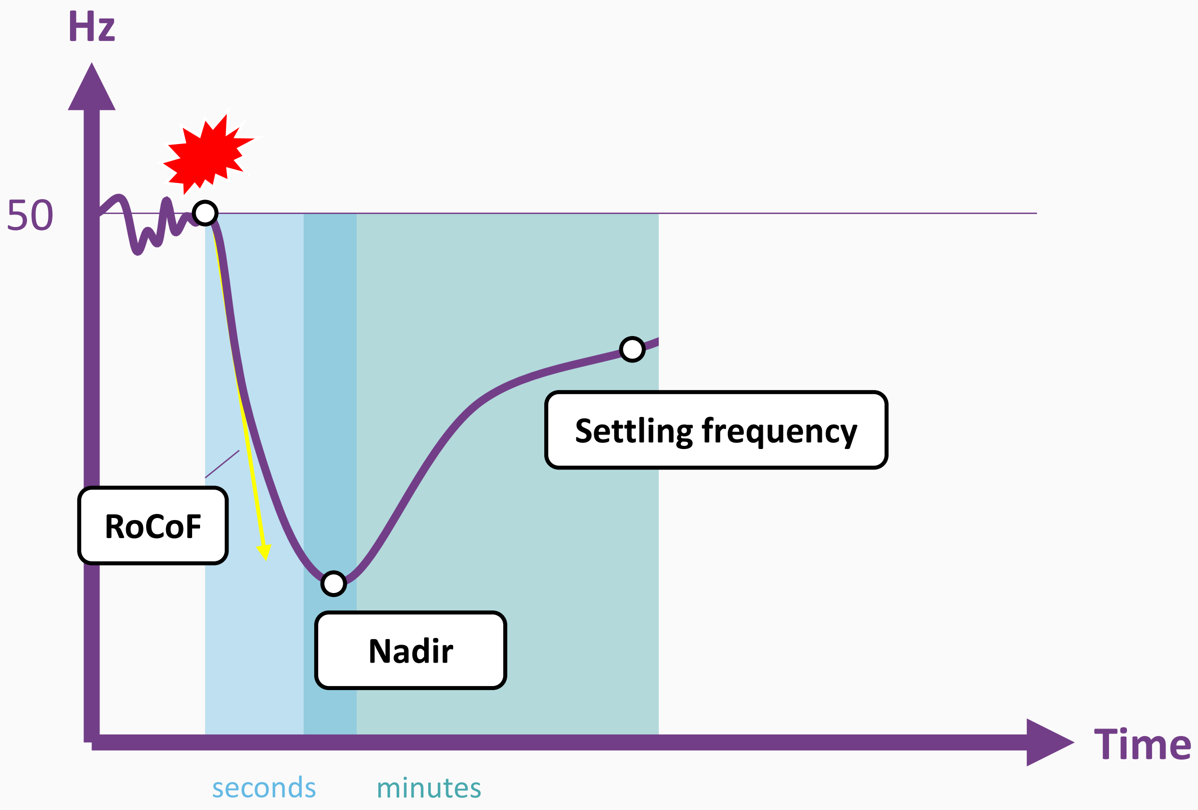
30s-15m

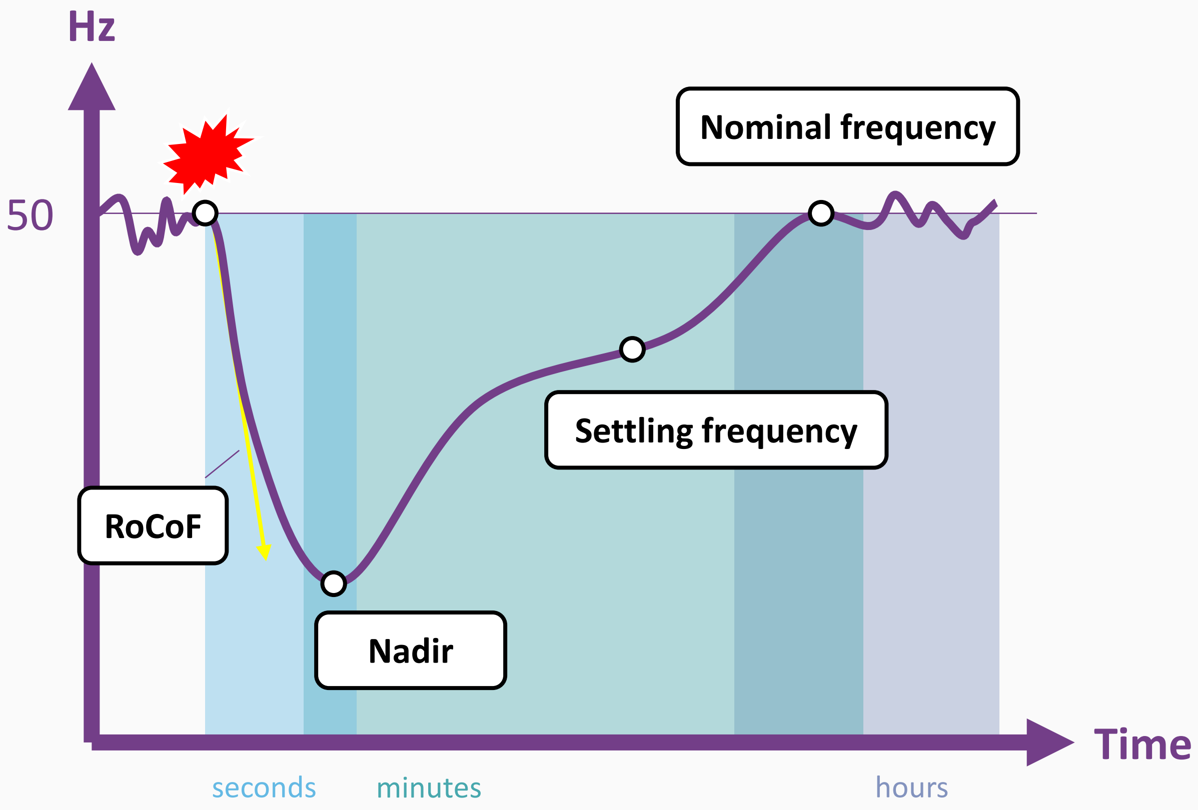
Frequency control step 2: automatic restoration or secondary response



- Other plants, also equipped beforehand, can receive a signal from the system operator to automatically adjust their output too.
- These plants often have slightly slower response times but can maintain their output for longer.
- These secondary reserves take over from primary reserves and are tasked to bringing frequency back to normal level (settling).

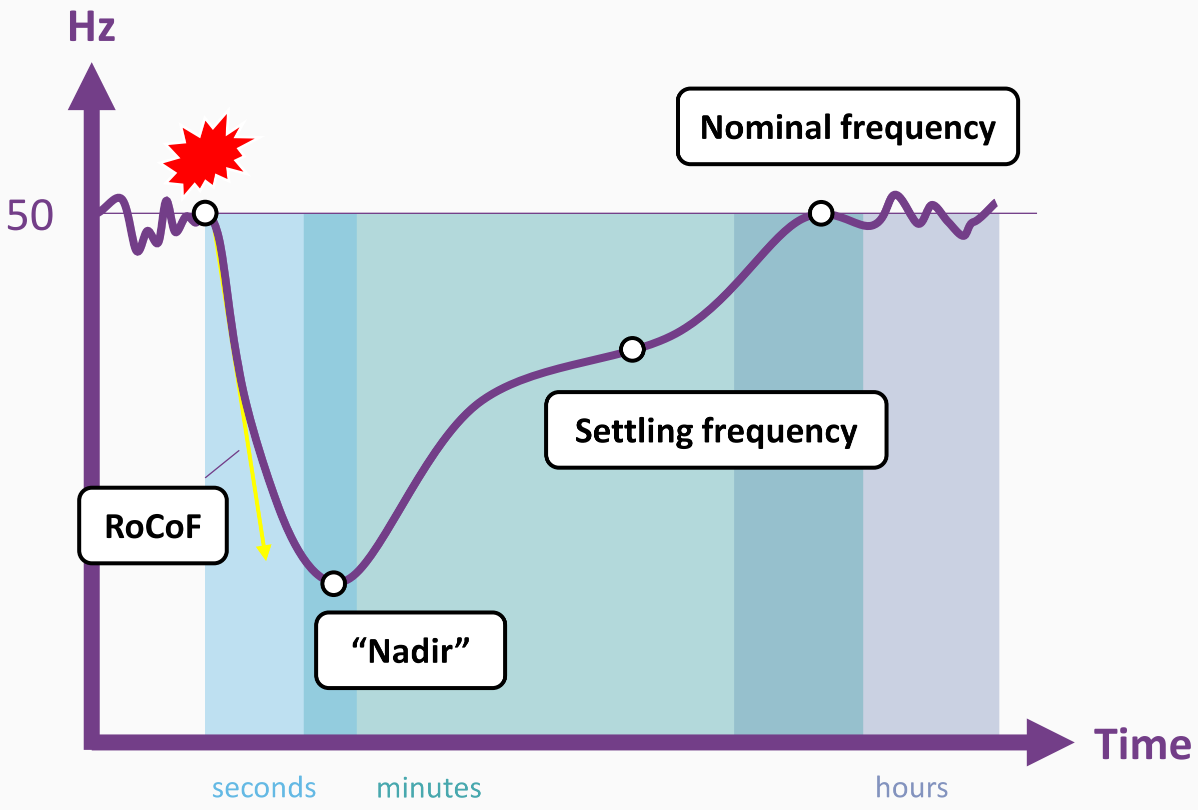
5-30m

Frequency control step 3: manual restoration or tertiary response



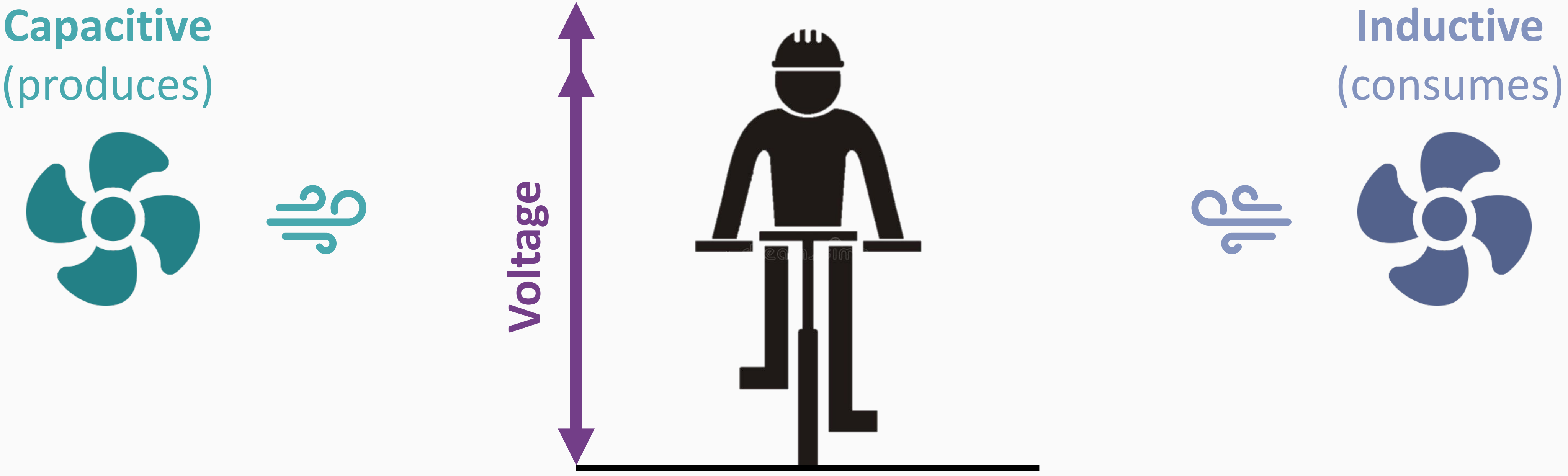
- → If needed, the system operators can contact some generators and ask them to adjust their output.
- → This can potentially be contracted beforehand.
- → Because it takes a manual action, Tertiary reserves take time to either get started, or to increase output.

Frequency control step 4: replacement



- Finally, the manual frequency restoration reserves (mFRR) are relieved.
- This can be done by activating specific reserves or by updating the economic dispatch (regulated or market-based).

Reactive power is blowing in the wind



Like for frequency, operators used a tiered-control approach

"Primary voltage control"

- **"Automatic Voltage Regulator (AVR)"**
- A **localized control** scheme implemented at individual power plants. The AVR continuously monitors the voltage at the generator terminals and automatically adjusts the generator's excitation system to maintain the voltage at a desired setpoint.
- This ensures that the generator injects power at the correct voltage level into the transmission grid.

"Dimmer for 1 lightbulb"

"Secondary voltage control"

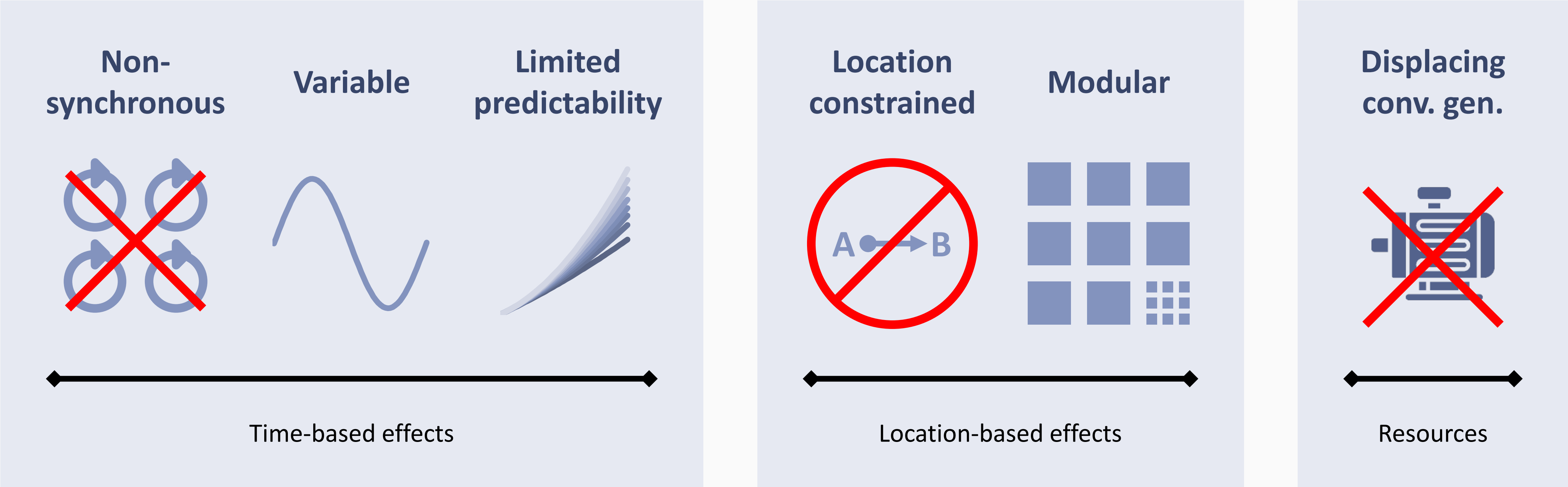
- Secondary Voltage Control (SVC)
- A **wider-area control** scheme that focuses on regulating voltage at specific points within the transmission network to ensure consistent voltage levels throughout the transmission grid.
- Secondary voltage control utilizes various **FACTS*** devices, like **Static Var Compensators (SVCs)** or capacitor banks, to manage reactive power flow and maintain voltage within predefined limits across the entire system.

"Master dimmer for the house"

 | * FACTS = Flexible AC Transmission Systems

As we move to a power system dominated by solar and wind (and other inverter-based resources), we have to deal with new challenges

Variable renewables, like solar and wind, have characteristics that challenge traditional operations & planning practices



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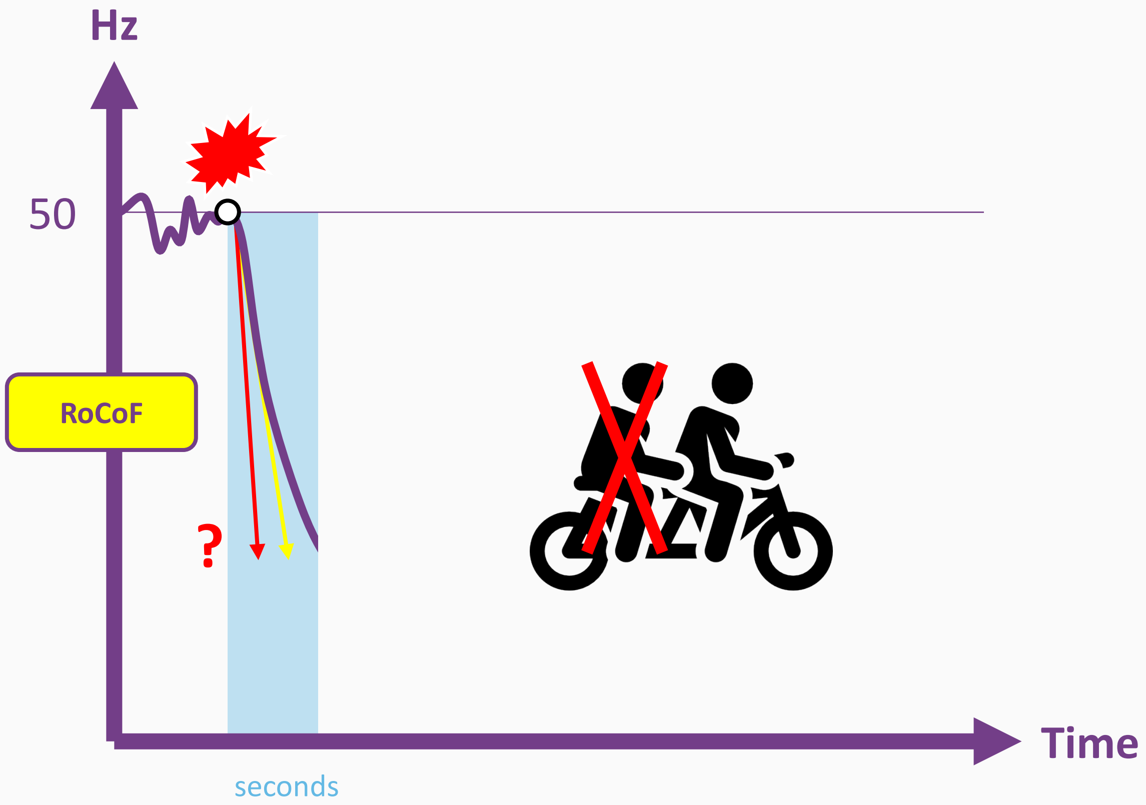
How high VRE shares shift the balance in terms of power system stability

- **Lower inertia:** solar and wind inverters don’t carry heavy spinning parts, so frequency can swing faster
- **Less fault-current and synchronizing torque**: makes clearing faults and keeping machines stable tougher
- **Remote Siting**: many renewables sit far from cities, stretching long lines and creating weak spots
- **More Cross-Area Flows**: can amplify inter-area oscillations if not managed

 | Photo by Andreas Gücklhorn (https://unsplash.com/@draufsicht) on Unsplash

VRE and frequency control: non-synchronous



Adding VREs can **decrease the system's inertia**

→ Inverter-based resources do not (automatically) contribute to the system's inertia

→ VRE displaces conventional generators, which are the main conventional sources of inertia

This can lead to a **higher Rate of Change of Frequency**

→ System operators worry that the frequency will change too quickly for reserves to kick in and contain the frequency deviation

→ If this happens, supply interruptions could happen (blackouts, brownouts)

Various technologies can deliver power system stability services

- **Grid-forming inverters (IBRs):** provide inertia, voltage support, and fast frequency response
- **Synchronous generators and condensers:** offer true inertia, fault-current support, and reactive power
- **Battery energy storage systems (BESS):** deliver ultra-fast frequency response and inertia emulation
- **Flexible AC transmission (STATCOMs, SVCs):** regulate voltage dynamically and damp oscillations

Photo by Arno Senoner (https://unsplash.com/@arnosenoner) on Unsplash

Agora's 2024 publication "System stability in a renewables-based power system" provides more in-depth examples

Download our power system stability report:

- The publication can be downloaded HERE
- For an overview and the key findings, see HERE
- A webinar recording based on the publication can be accessed HERE

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