SVENSKA KRAFTNÄT

Power system operational security

- future needs and abilities

AUGUST 2025

Contents

Introduction

Foreword

To achieve the transition to a fossil free energy system, the use of electricity will need to increase radically as forecasts and political objectives all point to a doubling of Swedish electricity consumption by 2045. The power system is also in transition as the properties of electricity generation and consumption change when they are connected using power electronics, and as the volume of weather-dependent electricity generation increases continuously. At the same time the power system must remain reliable throughout the year in both normal conditions and under stress, which creates new challenges for operational security in a future that will see an increasingly electricity-dependent society.

The increased complexity of the power system means that Svenska kraftnät needs to use a combination of different tools to effectively maintain operational security. These tools will become increasingly essential.

Stronger collaboration with industry players at all levels is a vital piece of the puzzle in delivering the required changes effectively. Svenska kraftnät is responsible for monitoring the electricity system's security of supply target set by Parliament, and for implementing or proposing the necessary measures to meet this target. We are also responsible for planning the electricity system, in which operational security is an important aspect.

This report examines the operational security of the power system and identifies the needs and abilities required in the future. I hope that this report will provide a clearer picture of Svenska kraftnät's work to maintain operational security in the power system and what needs to be done to create a reliable electricity supply.

Viktoria Neimane
Senior Vice President,
Power System Development

About this report

Welcome to Svenska kraftnät’s report on operational security in the power system of the future

The power system is undergoing a major transformation regarding both electricity generation and consumption. This report aims to provide insight into how this transformation impacts operational security and stability within the power system, and to outline Svenska kraftnät’s intended approach for managing these changes. A reliable and stable power system is a system that can withstand disturbances and return to normal operation as quickly as possible.

The report outlines future power system needs based on the changes occurring within it. To address these needs and ensure operational security, the system must possess various abilities. Different electricity generation methods have varying system support abilities. These abilities can be accessed in multiple ways, including through establishing requirements or incentives. In this report, Svenska kraftnät wants to describe existing needs, solutions and tools and what we will undertake in the future to ensure a reliable and robust power system. The report contains qualitative assessments of needs and abilities.

Operational security alone is insufficient for the power system to meet societal needs; adequate grid capacity and sufficient electricity generation are also required. In this report, we have chosen to focus on operational security. Other aspects that affect the security of supply of the power system are dealt with in other reports, which are presented in summary on the next page.

This report is aimed at readers who are interested in the power system but are not completely familiar with the technology and who want to get an overview of operational security and system stability going forward. This report aims to present complex technology in an accessible manner, it consequently avoids deeper technical detail.

Summary of analyses and reports

The reports can be found at svk.se and at the European Network of Transmission System Operators for Electricity, entsoe.eu

Long-term scenarios

Svenska kraftnät:

- Långsiktig marknadsanalys 2024
  [Long-term market analysis 2024]

ENTSO-E:

- Ten Year Network Development Plan 2024

TYNDP // 2024

Scenarios Report

Needs assessments

Svenska kraftnät:

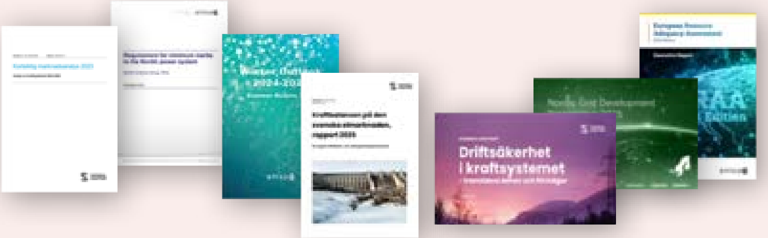
- Driftsäkerhet i kraftsystemet 2025
  [Power system operational security 2025]
- Kortsiktig marknadsanalys 2024
  [Short-term market analysis 2024]
- Kraftbalansen på den svenska elmarknaden 2025
  [The power balance in the Swedish electricity market 2025]
- Balancing market outlook 2030

Nordic:

- Nordic Grid Development Perspective 2025
- Requirement for minimum inertia in the Nordic power system 2023

ENTSO-E:

- European Resource Adequacy Assessment 2024
- Winter Outlook 2024–2025

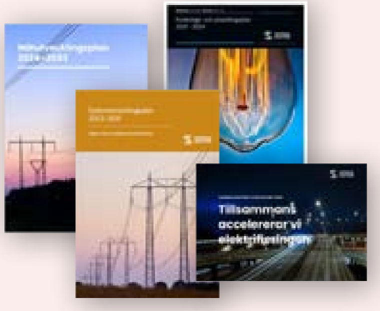


Driftsäkerhet i kraftsystemet

Strategy and plans

Svenska kraftnät:

- Svenska kraftnäts strategi mot 2030
  [Svenska kraftnät's strategy for 2030]
- Nätutvecklingsplan 2024–2033
  [Grid development plan 2024–2033]
- System Development Plan 2022–2031
- Forsknings- och utvecklingsplan 2021–2024
  [Research and Development plan 2021–2024]



Tillsammans accelererar vi elektrifieringen

KEY TAKEAWAYS

Driving changes and the need for measures

- The power system is becoming more complex as electricity generation and consumption are increasingly connected using power electronics. Electricity generation will be more weather-dependent but also more distributed, with more generation located further out in the system.
- Uncertainties regarding future electricity demand, as well as the technical characteristics and behaviour of generation, result in that Svenska kraftnät needs to plan and allow for an increasing number of different situations and outcomes. It must be possible to handle every outcome while maintaining operational security.
- Svenska kraftnät will need to manage a system with a large proportion of weather-dependent generation in the future, both before and after any new nuclear power is in place.
- With a society that is becoming more and more dependent on electricity, the efficient management of the emergency operation and restoration of the power system is increasingly important, especially in the event of sociopolitical crises and, ultimately, in the event of war.

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- Svenska kraftnät works with an extensive toolkit to maintain adequate operational security in all operating states. These tools include investment in infrastructure, establishing suitable requirements for third-party facilities, and utilising market-driven procurement and financial incentives.
- Further measures are required to ensure operational security across all future operational conditions and societal circumstances, with measure selection guided by socioeconomic considerations.
- It is important that all parties and generation categories in the power system contribute abilities and flexibility according to their individual circumstances. As the transmission system operator, Svenska kraftnät is responsible for leading the various power system stakeholders through increased cooperation, incentives and specified requirements.
- Synchronous generation contributes important abilities to the power system, now and in the future. Non-synchronous facilities can also contribute similar abilities provided that the right set of requirements and incentives are in place.
- Innovation and the development of technology are important for the power system of the future, and Svenska kraftnät, together with other stakeholders, needs to continue to evaluate how new technology with its new abilities can contribute to operational security.

A power system in transition

Increasing demand with large uncertainties ahead

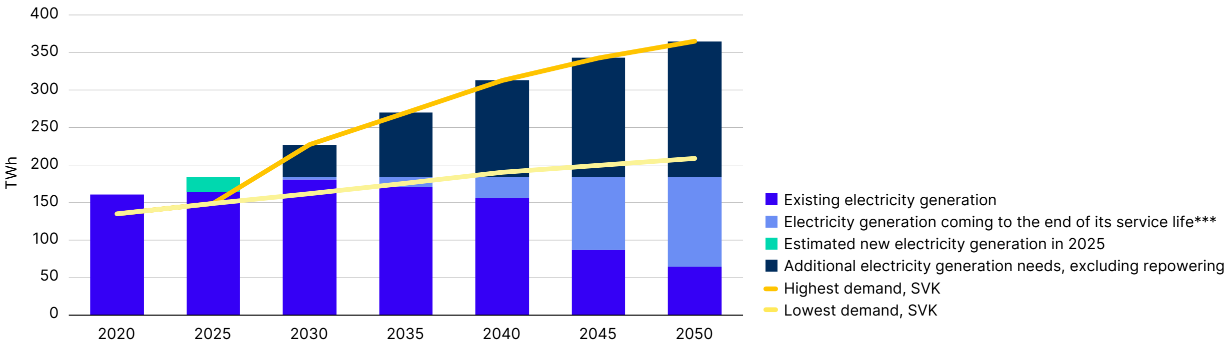
Over the past 10 years the power system has evolved. There has been a significant expansion of wind power and the proportion of renewable electricity in the Swedish power system has increased. Over the same timeframe, multiple nuclear reactors have been decommissioned. Today, electricity generation in Sweden is essentially fossil-free and is based on wind, hydropower and nuclear power. An increasing proportion also comes from small-scale photovoltaic generation.

Sweden's electricity demand is expected to increase in both the short and long term. This increase is mainly due to industrial development with the increased production of, among other things, fossil-free steel, electrofuels and green hydrogen. There are major uncertainties regarding the outcomes of this development. Based on the latest scenarios developed by Svenska kraftnät these outcomes are given as a range.*

There are also uncertainties associated with electricity generation and its characteristics; the type of generation constructed, when this occurs and the location and size of facilities are all issues that affect the power system. Similar impact is expected from the likely increase of large electricity users.

Even if new nuclear power is developed in Sweden a significant amount of solar and wind power will be added to the power system. This means that a system with a large amount of variable and converter-connected generation** will need to be managed, both before and after any new nuclear power is in place.

Uncertainties in electricity demand as well as the technical characteristics and behaviour of generation present new challenges for Svenska kraftnät's planning. We need to plan in order to manage different types of outcome so that operational security can be maintained, regardless of what abilities will be available in the future. This means that measures and margins must be designed taking into consideration a broad spectrum of potential outcomes.

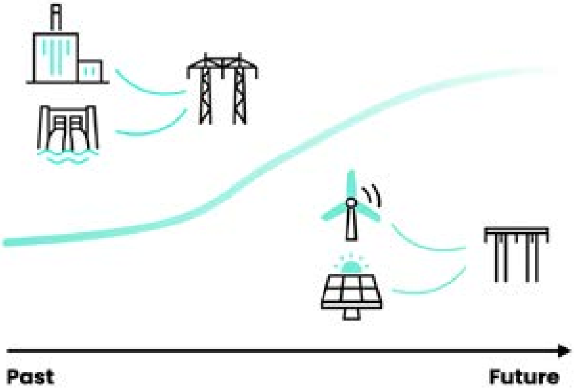


* Long-term market analysis, Svenska kraftnät, 2024
** The concepts variable and converter-connected generation are described in more detail on the following page
*** A service life of 60 years has been assumed for nuclear power

Several major changes affects security of supply

Changes in the generation mix mean that the power system has gone from mainly predictable generation with synchronously connected facilities, to a significant proportion of variable generation that connect to the electricity grid through power electronics-based converters. Generation connected via converters does not automatically provide the same abilities as synchronously connected generation, such as rotational energy. This creates new challenges for the security of supply and operational security of the power system. However, converter-connected and variable generation can provide important abilities, if the correct requirements are specified and if there are sufficient financial incentives to make their contribution profitable.

A large part of the additional generation is connected at the distribution grid level, unlike in the past when generation was most often connected at the transmission grid level. Among other things, this means that it will be more difficult for Svenska kraftnät to specify direct requirements related, for example, to voltage control and other necessary abilities, as this is carried out via grid owners at the distribution grid level. This may result in these abilities needing to be acquired through other, less efficient means. The demand side is also changing with several large load facilities connected to the power system such as hydrogen production and data centres.



Dispatchable generation refers to electricity generation that under normal circumstances can be managed to a predetermined level, for example nuclear power, hydropower and thermal power. Predictable generation has access to stored energy in the form of reservoirs for hydropower or fuel storage for thermal power. Hydropower is often dispatchable, meaning that it is possible to decide relatively freely when and how much electricity to produce.

Variable generation, also called intermittent generation, refers to generation that is more difficult to manage to a specific level as available energy varies with external factors such as the weather. Variable generation consists primarily of wind and solar power. Variable generation can be controlled to some degree, but primarily through reducing output.

Wind and solar power are included in the **non-synchronously connected generation** category, in other words electricity generation that uses generators that rotate independently of the power system or do not rotate at all, and where power is supplied using power electronics. This type of electricity generation facility is also referred to as **converter-connected generation**. This is in contrast to hydropower and nuclear power that are **synchronously connected** to the grid, which means that generators physically rotate in step with the power system.

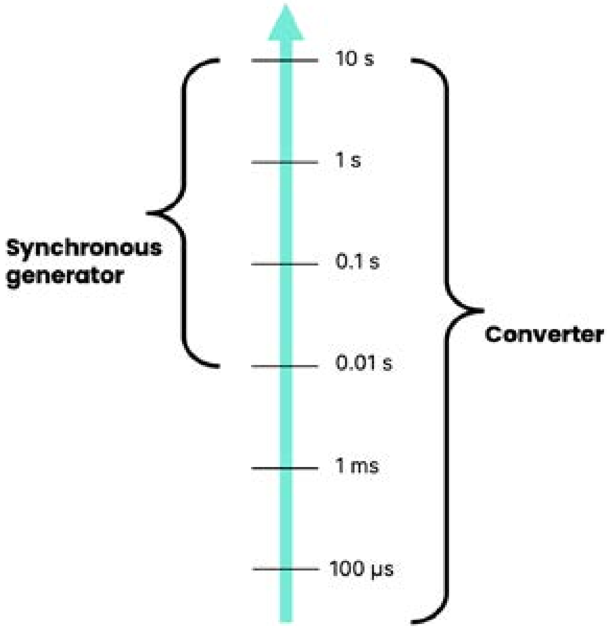
The dynamics of the power system are changing

The power system is dependent on connected facilities being able to contribute to the control of the power system's shared variables such as frequency and voltage, as well as active and reactive power. This control needs to work in different time scales, from fractions of a second upward.

Rotating machines such as synchronous generators effectively control, among other things, the voltage and frequency of the power system. Synchronous generators have electromechanical properties and dynamics that have historically been crucial for the stability and behaviour of the power system.

Wind and solar power are typically connected through power electronic converters. The dynamic characteristics of the converter depend entirely on its control, which provides great potential. The load connected to the power system is going through a similar transition, with a lesser proportion of directly connected rotating machines and more converter-connected load.

The growing number of converters alters the dynamic characteristics of the power system, where both challenges and solutions increasingly occurring on shorter time scales.



Converter
A converter is a unit constructed using power electronics. The unit converts direct current (DC) to alternating current (AC) or vice versa, depending on the area of application. It is often used as an interface to connect wind and solar power to the power system.

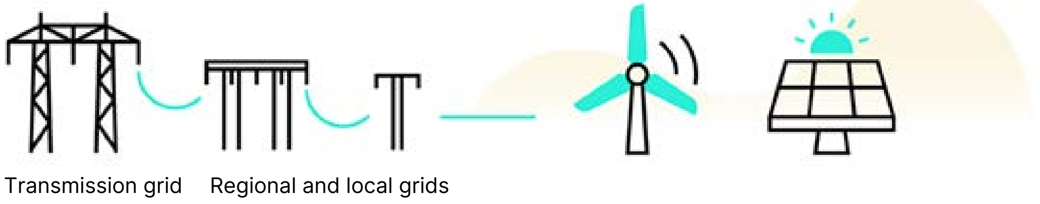
* Further information on this subject can be found in Nordic Grid Development Perspective, 2023

The power system is becoming more decentralised

Historically, the power system has largely been controlled and managed by relatively few parties with a clear division of responsibilities and a good ability to coordinate measures. The number of parties who own facilities and who participate in various markets is now increasing. Furthermore, it is becoming more common for plant owners not to maintain and manage the operation of their facilities themselves, but to hand over management to third parties. This development is expected to continue, leading to an increased need for coordination between all parts of the power system.

With an increasing share of electricity generation being connected to grid owners other than Svenska kraftnät, maintaining good operational security becomes increasingly challenging. Resources, important to the operation of the power system by contributing crucial abilities, are no longer regulated by Svenska kraftnät's requirements to the same extent. The responsibility for specifying requirements falls instead on the regional and local grid owners, who must take responsibility for their own operational security and for making the abilities of connecting facilities available to the power system as a whole.

In addition to this, some system needs are relatively local and need to be handled at a specific location, such as power line overloads or substation voltage levels. In such cases these need to be managed by nearby facilities. Other system needs, such as the active power balance for load-following and balancing, can be addressed from virtually any location in the power system. Nevertheless, this requires extensive coordination as ever smaller and distributed resources need to be utilised. This requires an increasingly clear division of responsibilities and improved coordination between Svenska kraftnät and other parties in order to guarantee adequate abilities in the power system.



As the transmission system operator, Svenska kraftnät is responsible for leading the various parties in the system through increased cooperation. Our role is to establish incentives for these parties through requirement specifications and market-based ancillary services.

All parties to the system need to be able to contribute to maintaining the operation of the power system. The affected parties must deliver the required abilities when and in the quantities needed by the power system, in accordance with regulations and contractual agreements.

Every technology - including nuclear power, wind power, and hydrogen production - must contribute abilities proportionate to their share of electricity generation and consumption within the power system.

System needs and abilities

Security of supply

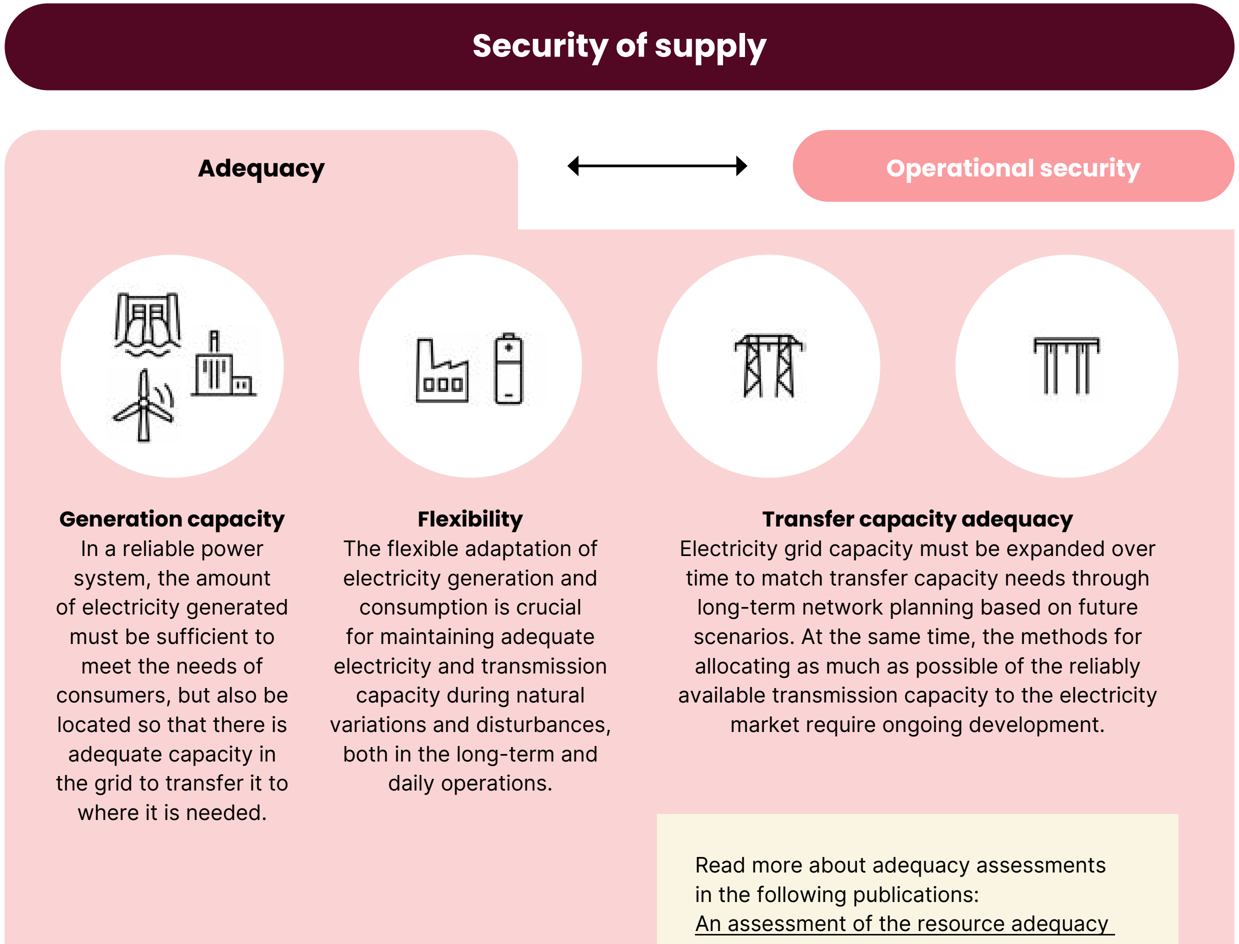
Security of supply describes the overall ability of the power system to generate and transfer electricity so that consumers can use the electricity they need, when and where they want to use it, even in difficult operating situations and with frequent disturbances.

Security of supply can be divided up into adequacy and operational security:

- **Adequacy** means that sufficient electricity generation and transmission capacity exists to fulfil consumer demand.
- **Operational security** ameans that the power system must be able to operate under normal conditions and be able to withstand stress in the form of different types of disturbance.

Adequacy and operational security are two goals that, to some extent, have an inherent conflict, as increased operational security can for example be achieved by limiting adequacy, through reduced transmission capacity. Svenska kraftnät balances operational security and adequacy based on risk and socioeconomic considerations.

This report focuses primarily on operational security.



Security of supply

Adequacy ↔ **Operational security**

Generation capacity
In a reliable power system, the amount of electricity generated must be sufficient to meet the needs of consumers, but also be located so that there is adequate capacity in the grid to transfer it to where it is needed.

Flexibility
The flexible adaptation of electricity generation and consumption is crucial for maintaining adequate electricity and transmission capacity during natural variations and disturbances, both in the long-term and daily operations.

Transfer capacity adequacy
Electricity grid capacity must be expanded over time to match transfer capacity needs through long-term network planning based on future scenarios. At the same time, the methods for allocating as much as possible of the reliably available transmission capacity to the electricity market require ongoing development.

Read more about adequacy assessments in the following publications:
An assessment of the resource adequacy of Swedish electricity supply, SVK, 2024
European Resource Adequacy Assessment, ENTSO-E, 2024
Long-term market analysis, SVK, 2024

Operational security

A reliable supply of electricity is crucial for society regardless of circumstances. A secure electricity supply must be maintained in peacetime as well as in a state of heightened readiness and war. **Operational security** means that the power system must be able to operate under normal conditions and be able to withstand stress in the form of different types of disturbance. The power system must be able to handle both small continuous fluctuations in operating conditions and significant individual variations and outages. Certain disturbances are so severe and rare that designing the power system to withstand them would be economically unfeasible; however, such events can result in widespread power outages. For this reason, being able to restore the system following a blackout is also included in the concept of operational security.

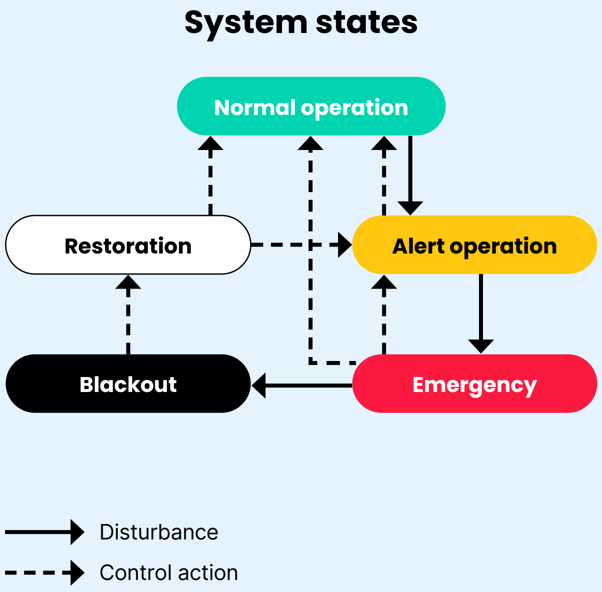
The extent of disturbance that the power system must be able to withstand is determined by the design criteria used. Svenska kraftnät's design criteria are based on the **N-1 criterion**, which requires the power system to survive any single disturbance that might occur within the system. Individual disturbances correspond to the loss of, for example, a cable or a generation facility.

Multiple simultaneous failures sharing a common cause may be addressed when their probability and impact are considered sufficiently significant. Several simultaneous but independent faults are not generally covered by the design criteria.

The N-1 criterion means that the power system has certain margins with which to endure disturbances, providing a basic level of **robustness** in the power system. Nevertheless, it is preferable for the power system to resist disturbances beyond those specified by the N-1 criterion, provided cost-effective measures are available. Such measures contribute to increased robustness.

The need for operational security in the power system can be divided into different **system needs**; these are described in more detail from page 24. In order to meet the system needs, various **abilities** are utilised to contribute to the power system. These abilities can be either the inherent properties of various types of technology or provided through requirement specifications and incentives. These abilities and how they can be provided adequately are described in more detail on the following pages.

A framework for operational security
Design criteria, together with operational security limits and system states, form part of the framework used by Svenska kraftnät to manage operational security in the national transmission system. The conditions necessary for implementing measures vary between different system states. All states have a technical requirement specification that describes how a facility should behave. In normal operation, optional measures such as markets and ancillary services contribute to operational security. During emergency and restoration, Svenska kraftnät has a greater mandate to employ compulsory measures to maintain operational security.


System states

System needs and abilities

The conditions for maintaining operational security can be described based on three different factors: **inherent** and **added abilities** and **system needs**. To maintain operational security, the power system's inherent and added abilities must exceed the needs for properties and functions needed to withstand specific types of stress.

Inherent abilities + **Added abilities** ≥ **System needs**

Inherent abilities refer to properties that exist in the power system and its connected facilities without the system being explicitly designed to have these properties. The inherent abilities are thus characteristics intrinsic to the connected facilities that can contribute to improving or degrading the stability and operational security of the power system.

Typical examples of such abilities are the mechanical rotational energy and fault current injection of synchronous generators as well as the frequency and voltage dependence of certain load facilities which react instantaneously to deviations in frequency and voltage respectively.

Added abilities refers to properties and functions that Svenska kraftnät and other actors have added to the power system that would not otherwise have existed, at least not to the same extent. Svenska kraftnät can provide abilities through investment in its own infrastructure and grid, requirement specifications as well as financial incentives and procurement.

Some added abilities are identical to or mimic inherent abilities, such as synthetic rotational energy, synthetic frequency-dependent load, synchronous compensators and the synchronous compensator operation of generators. Other abilities are always added, for example frequency and voltage control.

An operationally secure power system must be able to operate under normal conditions and be able to withstand stress in the form of different types of disturbances. This entails several different **system needs** in order to withstand variations in active and reactive power and other events that are beyond Svenska kraftnät's direct control. For example, this may involve natural power variations between generation and load, as well as major disturbances in one or more individual facilities. The behaviour of disturbances and natural variations in terms of size, duration and speed helps in assessing the needs related to measures and abilities.

Disturbances and variations can be influenced by requirement specifications and financial incentives, for example limits on ramping rates and imbalance fees.

Power system stability

If the power system’s need for a particular property is not met, the system may become unstable. Stability refers to a power system’s ability to maintain equilibrium and restore acceptable equilibrium conditions following a disturbance - for instance, keeping frequency within specified limits during and after the event.

Power system stability can be divided into five categories*. Of these, frequency and voltage correspond to well-defined physical quantities with defined target values. The target value for frequency is 50 Hz while the target value for voltage varies with the voltage level at each point in the grid. The remaining three stability categories - angular stability, resonance stability and converter stability - represent additional conditions that must be satisfied for the system to remain synchronised and well-dampened. The latter two categories have become increasingly relevant in recent years, as the share of converter-connected generation has grown.

Power system stability

Frequency stability	**Voltage stability**	**Angular stability**	**Resonance stability**	**Converter stability**
Frequency stability is the power system’s ability to maintain stable frequency both in normal operating conditions and after experiencing a disturbance.	Voltage stability is the ability of the power system to maintain acceptable voltages at all nodes in the system under normal conditions and after experiencing a disturbance.	Angular stability is the ability of generators to remain synchronised under normal conditions and after experiencing a disturbance. The concept also includes to dampen power oscillations between groups of generators in different geographic areas in the power system.	Resonance stability concerns oscillations in the power system in the frequency range 5–45 Hz. These unwelcome voltage and current oscillations can be electrical or electromechanical.	Converter stability describes undesirable interactions linked to the rapid dynamics of converter control functions. They must operate stably alongside other converters and power grid components.

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* The classification is based on: Definition and Classification of Power System Stability - Revisited & Extended, IEEE, 2021

Robustness

Robustness is a measure of how much stress the power system can withstand. A highly robust system can withstand large deviations from planned operating conditions. In the absence of robustness, deviating operational conditions may require transmission capacity constraints to ensure operational security. Robustness is therefore necessary to maintain security of supply.

The robustness of the power system is determined by Svenska kraftnät's design criteria. These criteria involve a compromise because too much robustness can signal an oversized power system or inefficient utilisation, leading to increased costs.

Svenska kraftnät's design rules are based on the power system being able to survive any single failure that could occur (the N-1 criterion). Multiple simultaneous failures sharing a common cause may be addressed when their probability and impact are considered sufficiently significant. This contributes to an extended level of robustness. Several simultaneous but independent faults (**N-X**) are not generally covered by the design criteria. Historically, however, the power system has in many cases still been so robust that it has been able to withstand much larger disturbances than it was designed for. An example of this is the disturbance on 23 April 2023 which is presented on the next page.

Fundamental robustness

Extended robustness

EXAMPLE

Disturbance 26 April 2023

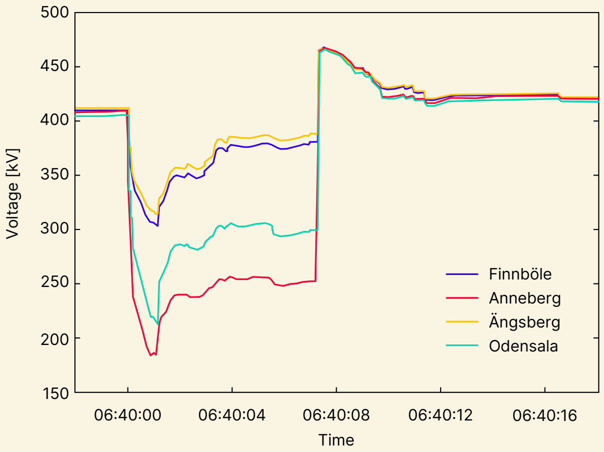
The disturbance at the Hagby substation in the spring of 2023 consisted of several independent and consecutive faults that led to an extreme strain on the power system.* Fault clearance and the associated low voltages typically impact the system for periods shorter than 0.2 seconds. In this case the voltage was very low for 7 seconds, and the dynamics and disturbance resistance of connected facilities were therefore of great importance. Due to the low voltage, two nuclear reactors were disconnected from the grid to protect the plants, resulting in lost power generation (over 2000 MW) far exceeding the dimensioning fault (1400 MW). While the voltage and active power disturbances surpassed the system's design limits, their overall impact on the power system remained relatively minor.

This event is an example of how voltage and frequency stability relate to disturbance resistance and how several stability phenomena can occur simultaneously. The disturbance significantly affected the frequency through active power imbalance but the outcome was mitigated by the voltage-dependent behaviour of connected loads affected by the voltage disturbance. In a situation with tighter margins and less robustness, the disturbance, which was far greater than the dimensioning fault, would have had a far more severe impact.

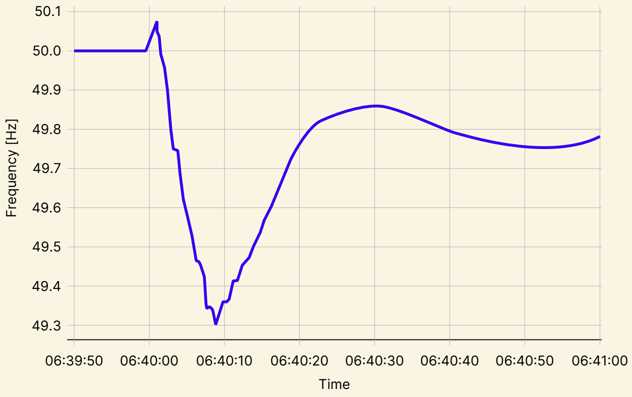
The robustness demonstrated during the disturbance was largely due to the substantial inherent abilities, such as mechanical rotational energy, that existed in the power system at the time. The event is therefore also an example of how a large amount of inherent abilities meant that in many situations the power system has historically been so robust that it could handle far greater disturbances than the N-1 criterion.

In a future power system, with a large amount of added abilities that must be designed on the basis of specific criteria, robustness is at the level for which the power system is designed. In that case it is critical to choose which disturbances can be managed, and how robust the power system should be.

Voltages in nearby stations during the disturbance



The effect of the disturbance on frequency



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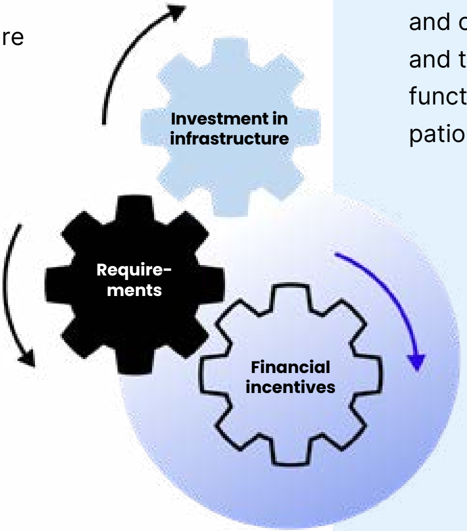
* The sequence of events during the disturbance is described in more detail in the report Disturbance 26 April 2023, SVK, 2023.

Svenska kraftnät's toolkit

Svenska kraftnät has a number of tools in its toolkit to meet the needs of the power system. The purpose of these tools is to add abilities and limit the magnitude of disturbances in the power system.

The toolkit consists of three components:

1. Investment in infrastructure and grid
2. Requirements
3. Financial incentives and procurement of abilities



When Svenska kraftnät identifies the need to add an ability to the power system, one alternative is to add the ability through investment in its own infrastructure. Svenska kraftnät can also choose to add measures through collaboration with other parties, in the form of requirement specification and financial incentives.

Investment in infrastructure and grid
For example, investment can be made by installing voltage control equipment in our own substations.

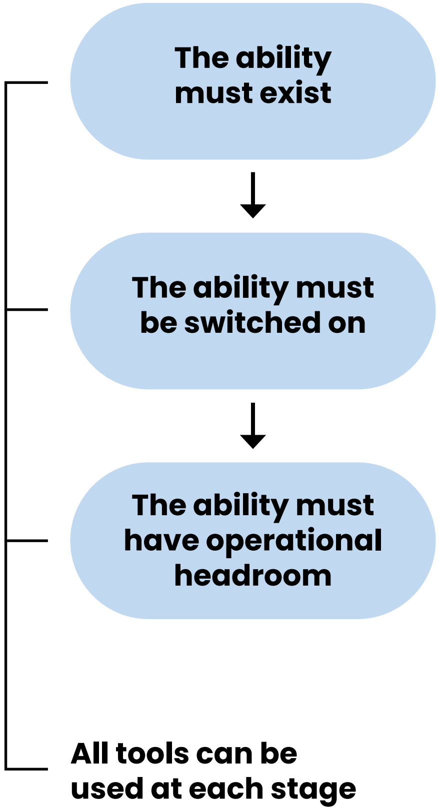
Requirements
Requirements can be specified by setting technical requirements for the connection and operation of facilities in the power system, and through market requirements such as functional requirements for market participation and imbalance management.

Financial incentives and procurement
The procurement of and payment for ancillary services is one example of a financial incentive for affected plant owners.

It is normal for several of these tools to be needed when implementing a measure.
For example, the procurement of ancillary services constitutes an economic incentive for the affected plant owners, at the same time as ancillary services are subject to extensive technical requirements to ensure their effectiveness.

It is also common for Svenska kraftnät to implement several measures based on different tools but with a similar purpose.
For example, Svenska kraftnät will install its own voltage control equipment while also requiring generation facilities to provide similar abilities through connection requirements.

Adding an ability



The ability must exist

The ability must be switched on

The ability must have operational headroom

All tools can be used at each stage

The first step in providing an ability is ensuring it exists in one or more components or facilities connected to the power system. This step is typically ensured by technical requirements in the connection process or by in-house investment.

The second step is ensuring the capability is activated - for example, that the relevant facility is connected to the system at the appropriate time and with the correct control system settings. This can be achieved through operational requirements or financial incentives for example.

The third step is ensuring that the ability has sufficient operational headroom by allocating the control margin in the relevant parameters such as active power. Allocating operational margin is one of the purposes of ancillary services procurement, but can also take the form of requirement specification or in-house investment.

EXAMPLE

Grid forming converters

Grid forming converters can be described as a new generation of control technology where converters can provide fundamental abilities to the power grid. Control can be designed to mimic the physical characteristics of synchronous generators and to exploit the potential of the converters to meet system needs. All stability categories are affected by this change and most depend on converters being grid-forming in order to enable a greater proportion of converter-connected resources.

How grid forming properties are defined is crucial to the role converter-connected installations can play in the operational security of the future power system. This definition can be applied to in-house investment, is central to specifying requirements for third party facilities and forms the basis for ensuring that the right abilities are in place to meet the needs of the system through financial incentives.

In this case, the existence of this ability means that property definitions are established between manufacturers and system operators through direct dialogue or via connection codes and implementation guides. Ensuring that this ability is switched on and have operational headroom in this case means that Svenska kraftnät is investigating the most appropriate tools to ensure correct grid-forming properties are available.

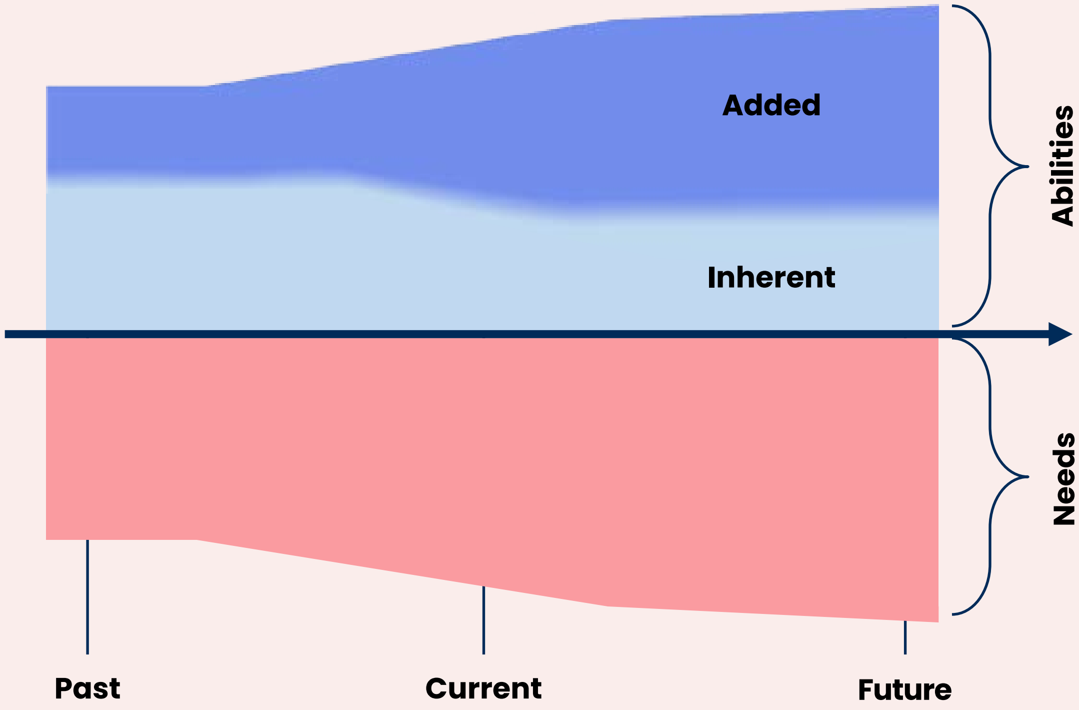
Synthetic rotational energy: With new types of control, the energy buffer in rotating wind power turbines could be made available as an additional ability in the power system, providing damping and rapid frequency control for example. The abilities of other resources with an inherent energy buffer, such as batteries and hydrogen production with storage, could be made available in the same way.

The development of operational security over time

Needs will change over time and with them the abilities necessary to maintain the robustness of the future power system. The graph illustrates a development in which the need for abilities that ensure operational security increases over time. As the power system transitions from primarily large-scale, plannable, synchronous generation to more decentralised, variable, converter-connected generation - with electricity consumption doubling - operational security faces multiple impacts.

When the proportion of synchronously connected generation with inherent physical abilities decreases, the power system undergoes a shift that invalidates traditional assumptions. The characteristics and quantity of inherent abilities change while the needs simultaneously increase in scale and evolve. Added abilities will play a greater role than before, regardless of what the future generation mix looks like.

The following elements are crucial to ensure the abilities needed to maintain robustness and operational security: updates to today's ancillary services; a more extensive set of requirements for adding abilities; and a significant increase in Svenska kraftnät's in-house investment.



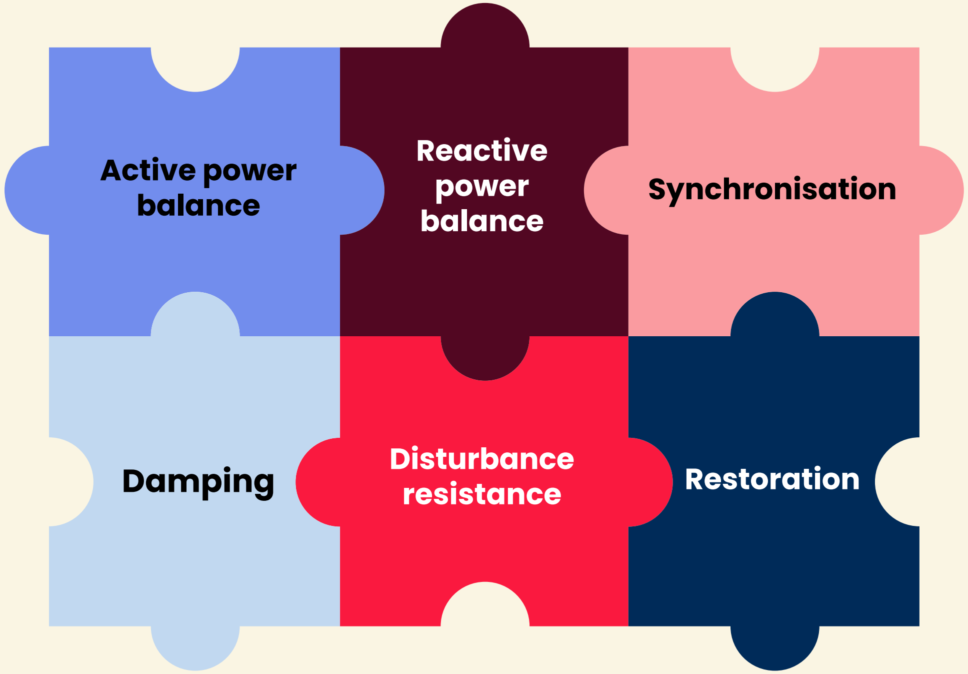
Description of system needs

Description of system needs

For the power system to be reliable in the future, a number of system needs have to be managed.

This report describes system needs based on six categories: Active power balance, Reactive power balance, Synchronisation, Damping, Disturbance resistance and Restoration.* The needs sometimes overlap and interact with each other.

For each system needs, this section describes the need itself, current implemented measures, and future developments with necessary measures.



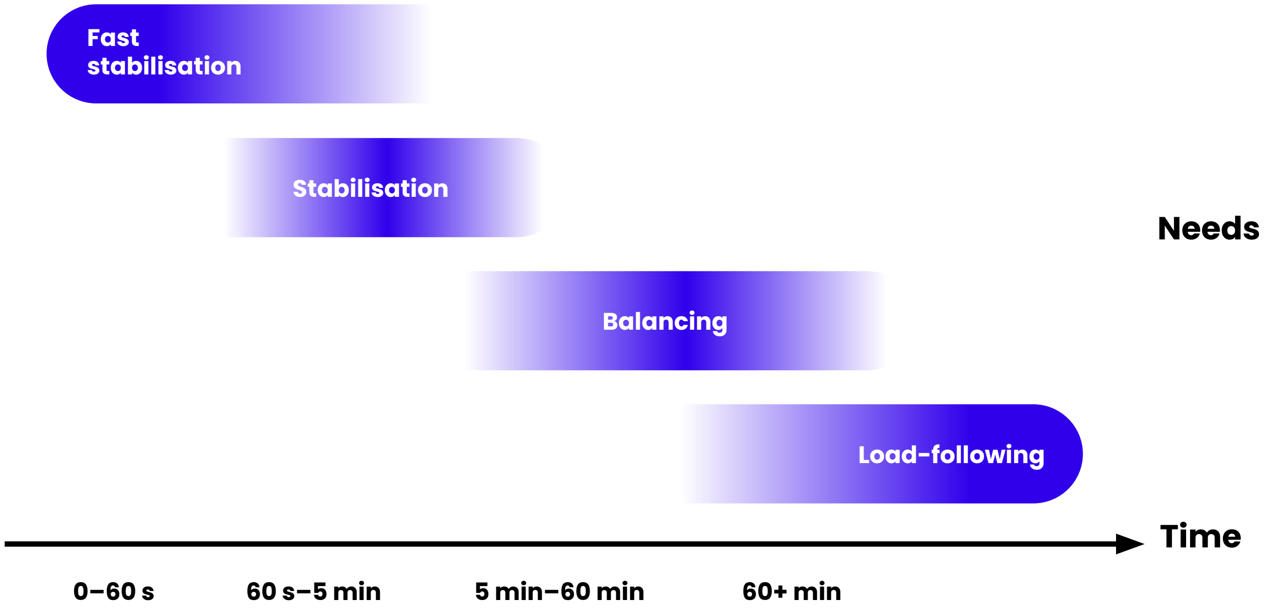
* The classification is inspired by the report System Needs and Services for Systems with High IBR Penetration, Global-PST, 2021

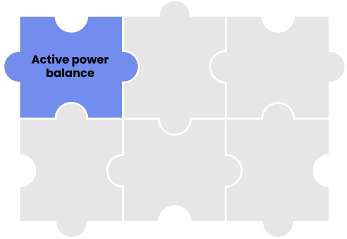
Active power and frequency

At any given instant active power generation must equal power consumption. Changes in active power generation or load are immediately balanced by increases or decreases in the rotational energy of rotating masses. Subsequently, Svenska kraftnät's stabilisation reserves activate to stabilise frequency, followed by slower balancing reserves that restore equilibrium between dispatchable generation and load and replenish the stabilisation reserves. On longer time scales, the electricity market maintains energy balance through load-following.

A more in-depth description of frequency control in the Nordic countries can be found in the report Overview of Frequency Control in the Nordic Power System. More information on market-based active power and frequency measures can also be found in the publication Balancing market outlook 2030.

Note that the balance settlement has switched to a 15 minute settlement period (in March 2025), but despite that the need for balancing often extends over several 15 minute periods and up to a few hours.





Fast stabilisation

Description

Fast stabilisation refers to the need to ensure that, in conjunction with rapid variations in active power, frequency is kept within set limits. Fast stabilisation handles very short time scales, from instantaneous deviations up to approximately 1 minute. Historically, Svenska kraftnät has relied on the rotational energy of synchronous machines, the contribution from the frequency dependence of load facilities, and the ancillary service frequency containment reserve for disturbances (FCR-D) to meet the need for fast stabilisation.

Measures implemented

- Since 2020, the remedial action fast frequency reserve (FFR) has been used.
- Tools to monitor and forecast rotational energy have been introduced.
- The technical requirements for FCR-D have been updated.
- The requirements for Low frequency demand disconnection (LFDD) have been revised.

Future developments

The inherent ability of mechanical rotational energy may decline further over time, particularly if current nuclear power is phased out without replacement. In certain operating periods this decline would have an impact on stability and would therefore need to be managed. In that case, adding mechanical rotational energy would benefit the power system, and future nuclear power expansion could help maintain stability.

However, based on current long-term scenarios, Svenska kraftnät assesses that rotational energy will not reach critically low levels requiring additional mechanical rotational energy. Instead, other measures such as FFR and synthetic rotational energy from converter-connected generation can provide equivalent benefits for fast frequency stabilisation.

Future measures

Operational security can be maintained through other abilities similar to today's FFR, which is currently provided primarily by batteries at relatively low cost. In the future, the FFR technical requirements are expected to need revision toward a dynamic FFR to ensure the measure remains technically effective at higher volumes, for overfrequency events, and during emergency operation and recovery.

Beyond FFR, other possible measures include synchronous compensators, generator operating in synchronous compensator mode and synthetic rotational energy from converter-connected generation.

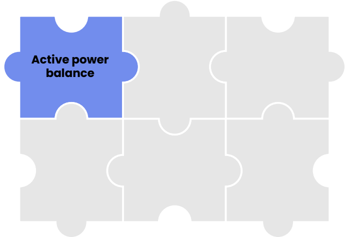
The measure ultimately chosen by Svenska kraftnät and other Nordic transmission operators will depend on what is most socioeconomically favourable given the actual outcome for natural rotational energy.

Rotational energy may continue declining over time, creating consequences that must be addressed during specific operating periods.

A number of different measures can be used to manage the consequences of declining rotational energy.

The Nordic transmission system operators will choose measures based on socioeconomic benefit.

Fast stabilisation Stabilisation Balancing Load-following



Stabilisation

Description

Stabilisation refers to dampening frequency variations to achieve a stable level, though not necessarily at 50 Hz. The stabilisation component that excludes fast-response needs operates on a time scale of approximately 1 to 15 minutes. Stabilisation is currently managed primarily through frequency containment reserves for normal operation (FCR-N), disturbances (FCR-D), frequency control in emergency state (LFSM and EPC), and the contribution from frequency-dependent loads. FCR-N and FCR-D are market-based products, LFSM and EPC are mandatory requirements, while load frequency dependence is an inherent ability.

Measures implemented

- The technical requirements for FCR have been revised (2023).
- Introduction of frequency control in emergency state (LFSM) at generation facilities.
- Proposal for revised connection requirements for generation submitted to the Swedish Energy Markets Inspectorate.

Future developments

The FCR-N volume is currently set at a fixed level of 600 MW, corresponding to the magnitude of continuous and rapid (<15 min) imbalances historically observed in the Nordic power system. In the future, this volume can be expected to increase along with total load. It is also likely that system needs will increase in line with an increased share of solar and wind power.

At present, the largest individual failures consist of large nuclear reactor units and HVDC connections to other synchronous areas. Even in the future, such facilities will continue to provide the design basis for FCR-D. Examples may include new large nuclear power plants, offshore and onshore wind installations, hydrogen production facilities, and HVDC interconnections.

The main source of frequency control in emergency state (LFSM), particularly for upwards effect, is currently hydropower, which generally provides a high degree of dispatchable generation. In the future, the availability of these emergency operation abilities may decline as the proportion of generation sources that typically operate near maximum output and that have limited dispatchability increases, such as nuclear, solar, and wind power.

Future measures

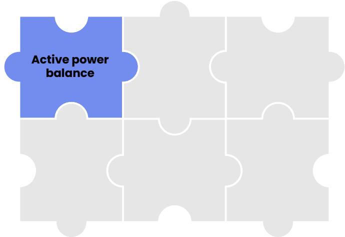
Introduction of LFSM for load, energy storage and HVDC connections.

Additional generation and load with energy storage must be capable of providing frequency control.

Requirement specifications need to be extended to ensure sufficient abilities during emergency operation and restoration.

Extended requirement specifications are also required for the abilities of large load facilities, energy storage and variable generation.

Fast stabilisation | **Stabilisation** | Balancing | Load-following



Balancing

Description

Balancing refers to the need to maintain an average frequency of 50 Hz over time. Since balancing refers to the average frequency value, it operates over longer time horizons, ranging from approximately 5 minutes to several hours. Balancing is primarily managed using automatic and manual frequency restoration reserves (aFRR and mFRR, respectively). Reserves are designed to deal with imbalances both during normal operation and in conjunction with design faults.

Measures implemented

- Technical requirements for ancillary services from variable generation or load resources have been introduced.
- Capacity markets for aFRR and mFRR ensure the availability of regulating capacity.
- Area-based balancing and energy markets for mFRR have been implemented within the framework of the updated Nordic balancing model (NBM).

Future developments

With regards to dimensioning faults, the development trajectory is expected to mirror that described for stabilisation, where dimensioning is based on large nuclear reactors, offshore and onshore wind installations, hydrogen facilities, and HVDC interconnections. For normal imbalances, the trend is similar to that previously described - imbalances are expected to rise in line with increasing electricity consumption. An increase in solar and wind power is also expected to drive a greater need for balancing, as variable generation resources often create significant imbalances on balancing timescales (>5 minutes).

The expected increase in electricity consumption makes hydropower, which historically has been the core balancing resource, a shrinking share of the total generation. Along with the increased balancing need the ability of hydropower risks being inadequate. The implementation of modern environmental regulations for hydropower will negatively impact its ability to contribute to grid balancing.*

Future measures

As hydropower's relative share declines, it becomes essential that all major new resources - including nuclear power, wind power, and hydrogen production - contribute proportionally, based on their capacity and abilities. These resources must be technically capable of providing frequency control and balancing services to ensure adequate availability of both upwards and downwards resources. This could necessitate connection requirements that address technical capabilities and, in the case of hydrogen production, possibly storage capacity as well. Additionally, markets, risk-sharing mechanisms, and financial incentives must be designed to encourage participation in balancing services.

It becomes essential that all major new resources - including nuclear power, wind power, and hydrogen production - contribute balancing abilities proportionate to their share of generation and electricity consumption.

There may be a need to impose enhanced connection requirements on new facilities concerning their technical abilities for grid balancing.

Modern environmental regulations will negatively affect hydropower's ability to provide balancing services.

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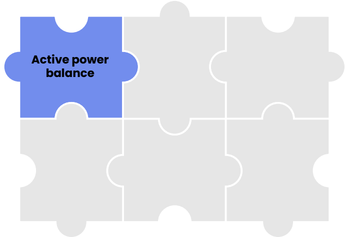
* Further reading: National effective access to hydropower electricity

Fast stabilisation | Stabilisation | **Balancing** | Load-following



Load-following

Description

Load-following refers to the ability of the electricity market to manage trading between participants through the day-ahead and intraday markets in order to reach the planned balance before the operating hour. While load-following is outside Svenska kraftnät’s direct area of responsibility, it is of relevance for frequency control because the same flexibility in consumption and generation forms the basis for supply, both in the ancillary service markets and for load-following. Consequently, there is a connection between supply and demand in all active power markets.

Future developments

Today, hydropower manages a large proportion of short and long term load-following in the system. A substantial part of additional future generation will be weather dependent, this will limit predictability and the capacity for flexibility.

The residual load, which can be explained simply as the consumption that must be covered by dispatchable generation, will progressively vary with the increasing proportion of renewable generation.

Future measures

To ensure sufficient resources for future load-following, it is essential that additional generation and load remain flexible. To address this need, both additional generation and new load require suitable abilities and incentives, similar to those used for balancing.

Flexible nuclear power generation may form an important part of the Swedish electricity market, especially if new nuclear power is deployed in Sweden. Load-following in nuclear power plants has been carried out in Sweden, mainly during the 1980s and 1990s. To enable flexible nuclear power generation, it is important that the design of any financial compensation mechanism for new nuclear power does not eliminate incentives or opportunities to provide flexibility.

Batteries are not expected to constitute a major source of load-following, particularly over longer time horizons (weeks, months, years), due to their limited energy capacity. At the 24-hour level, however, batteries can make some contribution.

As in the case of balancing, implementing modern environmental regulations for hydropower will negatively affect load-following capacity. It is therefore important that large generation and load facilities being built have the flexibility required to, together with imports, ensure sufficient load-following capacity.

Additional generation and load must be capable of providing flexibility.

When developing new nuclear capacity, it is essential to preserve both the incentives and the opportunities to contribute flexibility.

Batteries are not expected to constitute a major source of load-following over longer time horizons.

Implementing modern environmental regulations for hydropower will negatively affect load-following capacity.

Fast stabilisation | Stabilisation | Balancing | **Load-following**

Reactive power and voltage

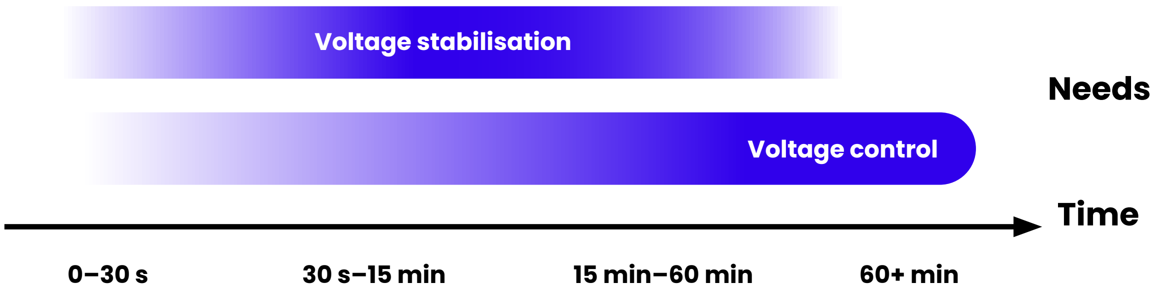
Voltages and reactive power flows must be continuously monitored and controlled in power systems to maintain secure active power transmission.

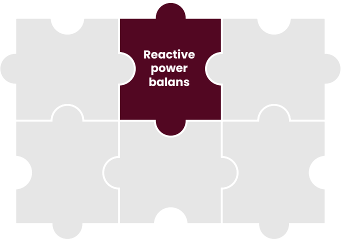
The voltage in the transmission system is primarily controlled by regulating the reactive power, however, the voltage is also considerably affected by the transmission and flow of active power. This means reactive power must sometimes be supplied during peak demand in the evening to maintain adequate voltage, and consumed during low night time transmission periods to prevent voltage rise.

The needs of the power system are mainly related to voltage, while the ability to manage and control reactive power can be considered a tool for achieving good voltage performance.

The needs and abilities related to reactive power and voltage can, just as for active power and frequency, be divided into different time scales. This breakdown can be approached in various ways depending on the level of detail required. This report focuses on the needs related to voltage stabilisation and voltage control as described on the following pages.

Reactive power
Reactive power refers to the component of electrical power that performs no useful work and occurs when voltage and current are out of phase. Power lines generate reactive power when carrying little to no active power. The greater the active power transmission, the more reactive power the lines consume. Reactive power significantly affects power system voltages. The supply of reactive power raises the voltage and consumption lowers the voltage.





Voltage stabilisation

Description

Voltage stability involves maintaining stable and acceptable voltage levels at all points of the system and ensuring that a new equilibrium can be reached following a disturbance. Voltage stabilisation is required across time scales ranging from very short durations up to at least 15 minutes. If this system need cannot be satisfied, transmission capacity is constrained from operational security. Load and generation may be disconnected as a result of a disturbance where this system need is not met.

Historically, voltage stability has primarily been supplied by synchronous generation facilities that control voltage and are directly connected to the transmission grid. Today, during specific operating periods there are few such facilities in operation, which leads to a reduced ability.

Measures implemented

- Svenska kraftnät have invested in and procured various voltage regulating resources, for example three STATCOMs (static compensators for reactive power).
- New principles for voltage and reactive power control have been developed together with the regional grid companies.
- Proposals for enhanced grid connection requirements for generation facilities and new requirements for battery storage systems have been submitted to the Swedish Energy Markets Inspectorate.*

Future developments

To ensure socioeconomically cost-effective voltage stabilisation in the future, the ability of large-scale generation connected to distribution systems to regulate voltage must be utilised. This applies to synchronous as well as converter-connected generation.

This ability also needs to benefit the entire power system. This means that tap changer operations on specific distribution system transformers (which control voltage transformation levels between grids, such as from 400 kV to 130 kV) require new coordination and control methods.

Future measures

- Continued analyses and investment in voltage control components. Implementation depends above all on where new generation and load are connected.
- Continued operational and strategic cooperation with regional grid companies. Contracts should be implemented to formalise agreements on large-scale distributed generation provision of voltage regulation and coordination of tap changer operations.
- By 2027, the transmission grid tariff is planned to include voluntary financial compensation for entities that provide voltage regulation at their transmission system connection points.
- New monitoring and tracking tools are being continuously implemented, utilising both measurement data and expanded data sharing with market participants.

Both converter-connected generation and synchronous generation, have a good inherent voltage controllability.

The ability to control the voltage of generation connected to distribution systems needs to be utilised.

* Svenska kraftnät's draft update of EIFS 2018:2

Voltage stabilisation
Voltage control

Voltage control

Description

Voltage regulation refers to the needs to maintain voltage levels within operational safety limits at all points in the power grid over time. In other words, voltage levels should not be too high or too low at any individual point, nor should there be large variations between different points in the grid. This needs applies over longer time scales, from minutes and upward.

Installations in the power system are designed for a certain voltage range. Voltage deviations outside acceptable levels reduce efficiency and may result in a shorter equipment service life and increased risk of system failure.

Reactive resources

Reactive power resources include components such as shunt reactors, shunt capacitors and series capacitors, with shunt components being particularly cost-effective. Reactive power resources also include dynamic voltage control equipment such as generation facilities, STATCOMs, synchronous compensators, and battery storage systems. These are more expensive but also provide greater support for voltage stabilisation needs.

Measures implemented

- Svenska kraftnät has invested in various reactive resources to provide the necessary abilities. In 2024, for example, an agreement was concluded for the delivery of a large number of shunt reactors (which help reduce voltage levels) to meet current needs as well as future needs arising from planned grid investments and new connections through 2032.
- Measures identified for voltage stabilisation also contribute to voltage regulation.

Future developments

Higher levels of active power requiring long-distance transmission through electricity grids necessitate additional reactive power resources to compensate for voltage fluctuations resulting from these active power flows.

As the power system's flows change in the future, both the location and the amount of reactive resources need to be continuously reviewed.

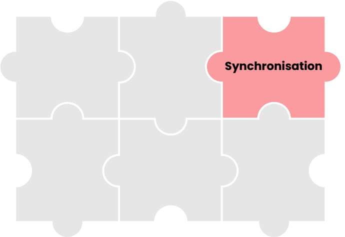
Future measures

- Starting in 2027, penalties may be imposed on market participants who cannot restrict their reactive power exchange with the transmission grid when this is requested by Svenska kraftnät. Less adverse reactive power exchanges provide improved voltage regulation.
- Continued investment in our own reactive resources is required. The need is primarily driven by the development of the transmission grid and where new generation and load are connected. The need is almost independent of the type of generation or load that is connected.
- Moreover, upcoming measures outlined for voltage stabilisation also contribute to meeting voltage regulation needs.

Increased active power transmission over longer distances requires additional reactive resources.

The most important measure going forward is continued investment in Svenska kraftnät's own reactive resources.

Voltage stabilisation Voltage control



Synchronisation

Description

For stable power system operation, both synchronous generators and converter-connected resources must remain synchronised with the power system. This means they must be able to handle various disturbances and variations in for example voltage and frequency at the point of connection without disconnecting.

A synchronous generator's inherent mechanical rotational energy contributes to grid synchronisation by not changing rotational speed instantaneously when a disturbance occurs. During a severe voltage drop at the point of connection, the synchronous generator's capability to deliver electrical power to the grid is reduced and the generator's rotational speed increases. The voltage at the point of connection must recover sufficiently quickly for the increase in rotational speed to be arrested and the generator to remain synchronised with the power system.

Conventionally controlled converters synchronise with the power system through measurements at the point of connection. The converter adjusts based on this measurement to achieve the desired power injection. In this way, the converter ”follows” the grid, which is why the converter control is called ”grid-following”. If the connection point is weak, it becomes more difficult for the converter to adapt quickly enough, since voltage variations become both larger and more rapid. A better approach for controlling converters is grid-forming control, which synchronises the converter through internal measurements. This control method provides improved converter synchronisation with weaker grids and enhanced capability to support island operation and grid restoration.

Measures implemented

Connection requirements have been developed for converter-connected facilities where synchronisation is ensured through other abilities, for example through increased fault tolerance.

Future developments

Converters connected to the power system have to a large extent implemented grid-following control. This has made several possible converter abilities unavailable.

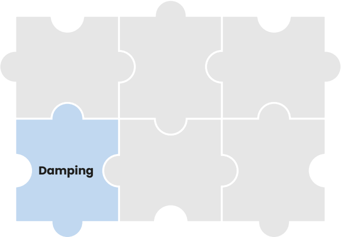
Growing needs for power system abilities in general, and converter abilities in particular, mean that grid-forming control functions will be necessary. To a large extent, this can be achieved through connection requirements.

Future measures

- Svenska kraftnät is working to develop requirements and compliance testing for grid-forming converters. The first phase involves developing requirements for HVDC converters (high-voltage direct current) and STATCOMs (static compensators for reactive power).
- The next phase will establish requirements for battery storage converters and solar and wind power converters. These requirements aim to ensure that converters maintain grid synchronisation under various connection point conditions and during system disturbances.

To ensure robust converter synchronisation in the future, a critical measure is to establish requirements for grid-forming control, and to some extent grid-following synchronisation.

Developing harmonised grid-forming requirements necessitates continued cooperation and collaboration within the Nordic region and with other sectors of the power industry.



Damping

Description

Frequency and voltage continuously fluctuate in power systems. During disturbances, these variables are affected and move toward a new equilibrium point. Under certain power system conditions, the new equilibrium may not be reached directly, instead oscillations may occur resulting. Damped oscillations diminish and settle to the new equilibrium, while undamped oscillations grow and may cause additional disturbances. Adequate damping requires oscillations to decay at sufficient rate.

Power systems dominated by synchronous generators exhibit relatively slow oscillations. Converter-dominated power systems face the risk of faster oscillations. This necessitates ensuring damping across a much broader frequency spectrum, creating new requirements for control systems and analytical methods for both operational monitoring and system planning.

Measures implemented

- Connection requirements for converter-connected generation and load have been established.
- Procedures for the detailed analysis of fast oscillations and system interactions have been developed.
- Updated FCR technical requirements include frequency oscillation damping specifications.

Future developments

The growing share of converter-connected devices in power systems will increase system complexity. Traditional methods for assessing the inadequate damping of fast oscillations are unsuitable for systems with a high share of converter-connected devices which requires new analytical approaches.

Future measures

- To enable converter abilities, grid-forming property requirements are under development. This work is proceeding in collaboration with other Nordic transmission system operators.
- Efforts are underway to develop monitoring and prevention measures for resonance and converter stability. A measurement infrastructure with sufficient bandwidth to observe these stability phenomena must be developed.
- Model verification and management work continues to enable more accurate detailed analyses and risk identification.
- Work is ongoing to revise the requirements regarding oscillation damping. For converter-interfaced facilities, this involves updated Power Oscillation Damping (POD) requirements to enhance their damping contribution.
- A potential FFR requirement revision is under investigation through Dynamic FFR, aimed at introducing fast frequency oscillation damping.

Clear converter requirements and power system integration specifications are essential for ensuring adequate damping.

Svenska kraftnät recognises the need for greater access to open-source models and data to conduct different types of detailed system studies.

Disturbance resistance

Description

Transmission system design criteria include the N-1 criterion, which requires the system to be designed for fault tolerance and capable of withstanding the loss of one arbitrary system component. Disturbance resistance also encompasses the needs that facilities and components connected to the power system must remain online and maintain synchronisation when parameters such as frequency or voltage deviate from normal values.

To ensure proper management of faults, such as short circuits in the power system, it is essential to isolate faulty sections quickly and safely. In the event of a fault, the fault current supplied by various facilities significantly affects the extent of disturbance propagation throughout the grid. Fault current is also necessary for protection systems to properly detect and clear faults.

Measures implemented

- Ongoing updates to connection requirements for generators and converters regarding fault tolerance.
- Currently working on establishing connection requirements for load facilities to ensure disturbance resistance, including tolerance to faults, overvoltage, and frequency fluctuations.
- The requirement specification regarding fault current injection from converter-connected production has been developed.

Future developments

At present, the disturbance resistance requirements primarily apply to generation facilities. As consumption increases and very large load facilities such as large-scale hydrogen production plants are added, it is important that they too have good disturbance resistance.

Some large load facilities will connect in clusters within relatively defined geographical areas. A disturbance in or near such an area can, if the load facilities lack sufficient ability to withstand disturbances, lead to more extensive disturbances with a significantly greater geographical distribution.

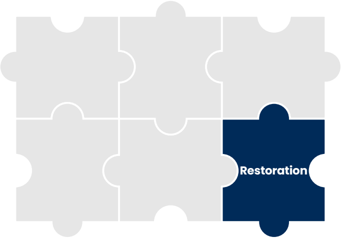
Svenska kraftnät continuously conducts fault current injection analyses at various grid locations for both current conditions and projected levels over the coming years. This also includes analyses of voltage restoration following a fault, where fault current injection is one of the factors that impact the sequence of events. Grid expansion that creates a more interconnected power system helps maintain fault current levels, as do properly designed converter requirements. It is also important to ensure that fault current levels do not exceed what the facilities are designed for.

Future measures

Svenska kraftnät is working toward further development and formalisation of requirements for load facilities regarding disturbance resistance.

The expansion of the disturbance resistance requirement also includes load facilities. Large load facilities mean new types of fault and their disturbance resistance is important.

Coordination of protection settings in large load facility connections to avoid unintended disconnection.



Restoration

Description

If the power system's operational security limits are exceeded, it can lead to partial or complete collapse of the power system. In such situations, the power system must be rapidly restored by reconnecting facilities, electricity generation, and consumption while maintaining stability to return the power system to normal operation.

The Emergency and Restoration code (ER) specifies requirements to ensure reliable, efficient, and rapid power system restoration. The goal of restoration is to safely and efficiently return to normal state, thereby minimising socioeconomic consequences.

Restoration requires special abilities such as black start and frequency control for example, with adapted settings during different phases of the restoration process. Restoration is facilitated by dispatchable generation, particularly if it is controllable. In Sweden, hydropower forms a cornerstone of the restoration plan, especially in its initial phases. During ongoing restoration and other types of crises, the island operation of individual regions may be necessary for preparedness.

It is essential that involved parties have a clear understanding of their roles and responsibilities during the restoration process. Training and exercises are needed to ensure that affected parties are well-prepared and can act appropriately.

Measures implemented

Svenska kraftnät has developed restoration and testing plans. The testing plan is used to regularly assess whether the measures included in the restoration plans achieve their intended effect.

Future developments

The amount of electricity consumption that needs to be reconnected after a grid collapse will increase in line with the growing electricity demand resulting from electrification. As hydropower's relative share of production decreases, other generation types will need to contribute more abilities and will be needed earlier in the restoration process to ensure adequate electricity generation.

New nuclear power in Sweden will also be an important resource. As will wind power, particularly if new nuclear power is not developed. Large electricity consumers may need to actively participate in restoration through flexibility and gradual start up of operations. Gas turbines could also contribute.

Future measures

- Expanded participation from variable generation and large electricity consumers.
- With increasing amounts of distributed generation, better tools and forecasting are needed to better predict the consequences of connecting different parts of the grid without jeopardising restoration.
- Enhanced requirement specifications for abilities along with sufficient staffing and expertise among grid companies and operators of variable generation and large consumption facilities.

The black start ability needs further development.

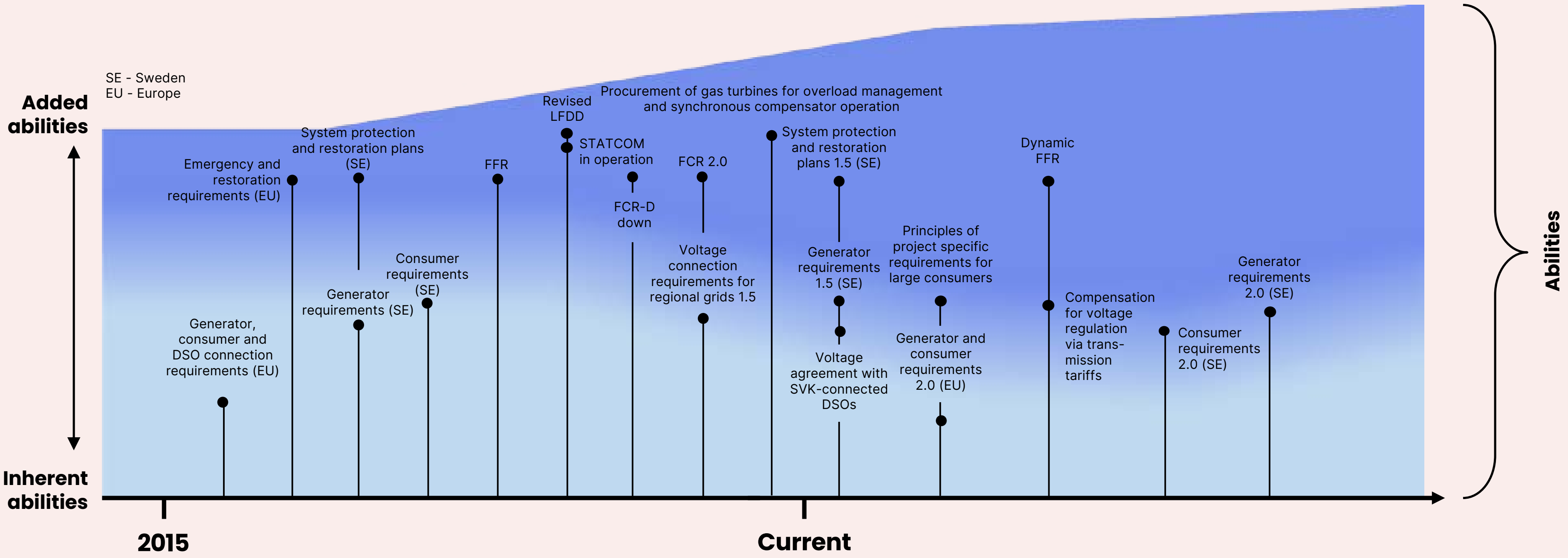
Continued training and exercises with the industry.

Access to existing important restoration resources needs to be secured (such as gas turbines).

Investigate possibility to add additional resources that can contribute to restoration (such as wind power).

Overview of implemented and future measures

As system needs increase, available abilities must grow to maintain the power system's operational security and robustness. Multiple types of measure are required to provide additional abilities and maintain inherent ones. Svenska kraftnät has access to various tools to achieve this: investment in its own equipment and grid, requirements linked to connection, operation and market mechanisms, or through economic incentives and the procurement of abilities. The figure provides an overview of measures implemented to date and future measures we are currently aware of.



Glossary

TSO – Transmission System Operator, owner and responsible for the operational security of the transmission grid

DSO – Distribution System Operator, owner and responsible for the operational security of the regional and local grids

FFR – Fast Frequency Reserve

FCR-D – Frequency Containment Reserve for disturbance

FCR-N – Frequency Containment Reserve for normal operation

aFRR – automatic Frequency Restoration Reserve

mFRR – manual Frequency Restoration Reserve

ADD – Automatic Demand Disconnection

LFSM – Limited Frequency Sensitivity Mode, frequency control in emergency state

EPC – Emergency Power Control, system protection scheme in HVDC facilities

HVDC – High Voltage Direct Current

NBM – Nordic Balancing Model, a new Nordic balancing model

STATCOM – Static Synchronous Compensator, facility for voltage support

POD – Power Oscillation Damping, converter-connected installations function to dampen power oscillations