ROBUSTNESS INDICATORS FOR POWER SYSTEMS

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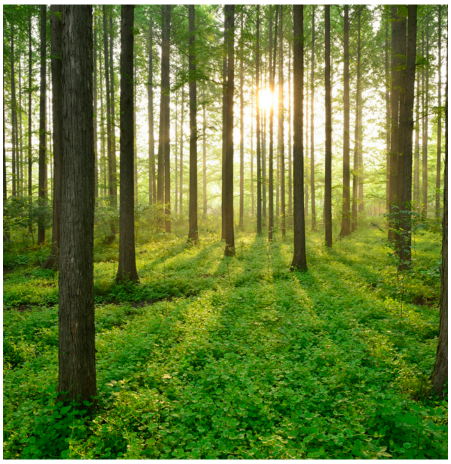
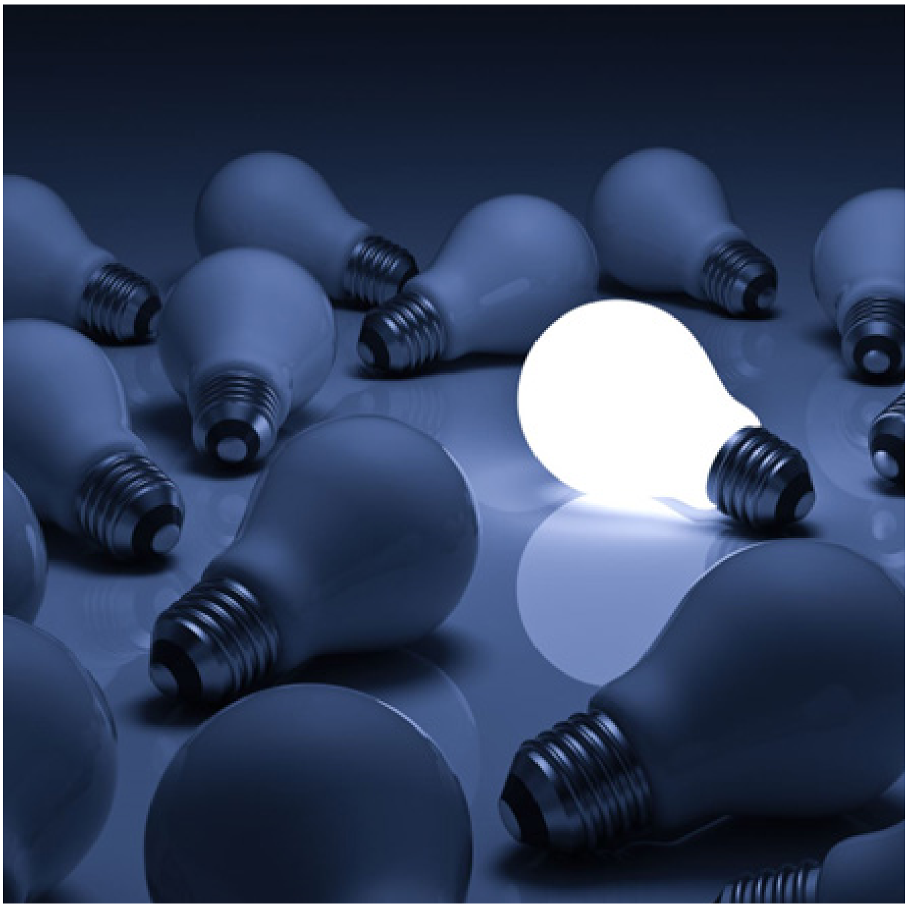


GRID INTERACTION WITH NUCLEAR POWER PLANT OPERATIONS, GINO



Robustness indicators for power systems

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Foreword

This report forms the results of a project performed withing the Energiforsk Interaction with Nuclear power plant Operations (GINO) Program. The Energiforsk GINO Program aims to increase the knowledge of aspects of the interactions between the external grid and the Nordic nuclear power plants. Part of this is to investigate technical issues.

The Nordic power system is undergoing significant transformations driven by the global energy transition toward renewable energy sources. This also brings changes in what can be called the system robustness - the system's ability to withstand an unexpected event without degradation in performance.

The purpose of this study was to investigate the possibility to develop relevant robustness indicators based on public data, with the aim to provide an improved view of the evolution of grid performance over time.

The study developed a framework and guiding principles that can be used to build indicators for different power system reliability aspects. The framework analyses a specific outcome, such as for example frequency or voltage quality, by developing indicators in each of four event categories; preconditions, unplanned events, measures taken, and outcome. The report also applies the framework to the above-mentioned outcomes and proposes further development as future work.

The study was carried out by Camille Hamon, Gustav Elfving, Erica Lidström and Simon Lindroth; Sweco Sverige AB. The study was performed within the Energiforsk GINO Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft, Karlstads Energi, the Swedish Radiation Safety Authority and Svenska Kraftnät.

These are the results and conclusions of a project, which is part of a research Program run by Energiforsk. The author/authors are responsible for the content.

Summary

An event chain framework for developing power system robustness indicators is proposed, where a particular outcome of the power system, such as frequency or voltage at a substation, can be thought of as the result of preconditions, unplanned events and measures taken by system operators. Power system robustness with regards to this outcome can then be measured by developing a set of as few indicators as possible covering each one of these categories. This framework is applied to frequency and voltage quality. A set of indicators is proposed and computed for each one.

Robustness is defined in the field of risk management as the ability to absorb shocks and continue operating. Within the context of power systems, there is no agreed-upon definition of robustness. However, well-established definitions exist for power system reliability, which can be divided into resource adequacy, power system security, power quality and, more recently, resilience. The multifaceted nature of power system reliability requires multiple sets of indicators to properly measure power system robustness in each of the reliability aspects.

The developed conceptual framework is backed up by a set of rules. First, each power system aspect should be described by as few indicators as possible to balance granularity and ease of understanding. Second, simplicity is prioritised so indicators can be understood without a deep knowledge of power system fundamentals. Third, data should either be available today or easily obtained. Fourth, it should be clear if an increase of each indicator is an improvement or a degradation of power system robustness, everything else being equal. Finally, indicators must be meaningful to follow trend over a time horizon of several years.

The event chain framework together with the guiding principles were applied to frequency and voltage quality. The selected indicators for frequency quality are monthly min/max values of the system frequency, monthly number of minutes outside of the normal interval, monthly and rolling 12-month average kinetic energy, total monthly absolute imbalance volumes and sum of activated frequency regulation reserve. For voltage quality, the selected indicators are min/max values, number of minutes outside of the normal interval, amount of available inductive and capacitive reserves and number of nodes with more than a pre-defined number of minutes outside of the recommended voltage interval. For voltage, it is proposed to further define the geographical region in which some of these indicators are computed.

The event chain framework and guiding principles make up a general set of rules that could be applied to any aspect of power system reliability. Application to other aspects than frequency and voltage quality is left as future work.

Keywords

Robustness indicators, quality indicators, power system reliability, indikatorer för nätrobusthet, tillförlitlighet.

Sammanfattning

Ett ramverk för att utveckla indikatorer för robusthet i elsystemet föreslås, där ett specifikt utfall av elsystemet, såsom frekvens eller spänning vid en transformatorstation, kan ses som resultatet av förutsättningar, oplanerade händelser och åtgärder vidtagna av systemoperatörer. Robustheten i elsystemet med avseende på detta utfall kan sedan mätas genom att utveckla en uppsättning av så få indikatorer som möjligt som täcker var och en av dessa kategorier. Detta ramverk tillämpas på frekvens och spänningskvalitet.

Robusthet definieras inom riskhantering som förmågan att absorbera störningar och fortsätta att fungera. Inom ramen för elsystem finns det ingen överenskommen definition av robusthet. Dock finns det vedertagna definitioner för leveranssäkerhet, som kan delas in i resurstillräcklighet, driftsäkerhet, elkvalitet och, mer nyligen, resiliens. Den mångfacetterade naturen av leveranssäkerheten kräver flera uppsättningar av indikatorer för att på rätt sätt mäta robustheten i elsystemet inom varje leveranssäkerhetsaspekt.

Det utvecklade ramverket kompletteras med en uppsättning regler som vägleder valet av de mest meningsfulla indikatorerna för ett specifikt utfall, såsom frekvenskvalitet. För det första bör varje leveranssäkerhetsaspekt beskrivas med så få numeriska indikatorer som möjligt för att balansera detaljnivå och förståelse. För det andra prioriteras enkelhet så att indikatorerna kan förstås utan djup kraftsystemskunskap. För det tredje bör data antingen vara tillgängliga idag eller lätt kunna erhållas. För det fjärde bör det vara tydligt om en ökning av varje indikator innebär en förbättring eller en försämring av robustheten i elsystemet, allt annat lika. Slutligen måste indikatorerna vara meningsfulla för att följa trender över en tidsperiod på flera år.

Ramverket för händelsekedjor tillsammans med de vägledande principerna tillämpades på frekvens- och spänningskvalitet. De valda indikatorerna för frekvenskvalitet är månatliga min/max-värden av systemets frekvens, månatligt antal minuter utanför det normala intervallet, månatlig och rullande 12-månaders genomsnittlig kinetisk energi, totala månatliga absoluta obalanser och summan av aktiverad frekvensregleringsreserv. För spänningskvalitet är de valda indikatorerna min/max-värden, antal minuter utanför det normala intervallet, mängd tillgängliga induktiva och kapacitiva reserver samt antal noder med mer än ett förutbestämt antal minuter utanför det rekommenderade spänningsintervallet. För spänning föreslås det att ytterligare definiera det geografiska område inom vilket några av dessa indikatorer beräknas. I båda fall beräknas indikatorerna numeriskt i den mån data har gjorts tillgängliga för detta projekt.

Ramverket för händelsekedjor och de vägledande principerna utgör en allmän uppsättning regler som kan tillämpas på vilken aspekt av leveranssäkerheten som helst. Tillämpning på andra aspekter än frekvens- och spänningskvalitet lämnas som framtida arbete.

List of content

1 Introduction

This aim of this project has been to develop robustness, or quality, indicators for power systems. The term robustness is usually defined in the field of risk management as the ability to absorb shocks and continue operating. Within the context of power systems, there is no agreed-upon definition of robustness. There is, however, an established framework of reliability and its classical aspects: resource adequacy, power system security and power quality. Recently, it has been proposed to add resilience as another aspect of reliability.

The proposed indicators in this project have been developed within this established framework. To fully capture the robustness, or quality, of power systems, it would be necessary to develop indicators for each one of the four reliability aspects (resource adequacy, power system security, power quality and resilience). Within the limited scope of this project, however, it has been decided to focus on power system security and, to some extent, power quality. Power system security and power quality can themselves be further broken down in different aspects. The project has investigated indicators for frequency stability and quality, and for voltage stability and quality.

This choice was made because of (1) the availability of historical data for these aspects and (2) the fact that these aspects have been well-established in the power system field for a few decades. In contrast, while there has been a well-established framework for resource adequacy for a few decades, it has only started to be used more recently by system operators. Data availability is therefore more limited. Resilience is a rather novel concept and there is no well-established framework used by system operators. Other aspects of power system security and power quality than frequency and voltage are crucial for capturing the full picture of robustness of power systems. However, data availability for these other aspects is limited. In addition, analysing these other aspects often require model-based simulations. In this project, the scope has been limited to indicators based on publicly available data, or data easily available on-demand.

Figure 1 illustrates the scope of the project within the framework of reliability. While the proposed indicators could be adapted to any region, the starting point in this project has been the Nordic synchronous area.

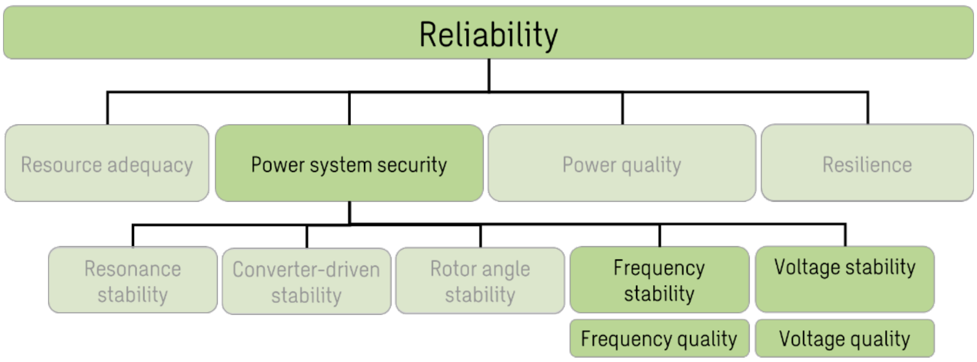

Figure 1: Different components of reliability. The scope of the project is highlighted.

Chapter 2 describes the established framework of reliability, as per Figure 1, and its different aspects in more detail. Chapter 3 reviews the existing regulation on power system reliability as well as existing indicators. Chapter 4 presents the framework and guiding principles that were developed in this project. Furthermore, the application to and visualization of indicators for frequency and voltage quality is presented.

2 Background

2.1 POWER SYSTEM STABILITY

Power system stability is defined in [1] as: "[…] the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

Historically, the three classic stability aspects have been rotor angle stability, voltage stability and frequency stability. Recently, with the emergence of new stability phenomena due to more converter-interfaced generation, FACTS devices and HVDC links, two other stability aspects have been added: Resonance stability and converter-driven stability, see Figure 2.

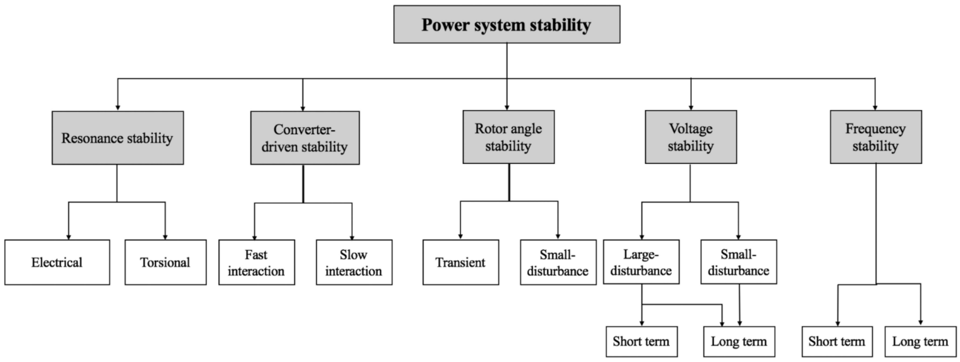

Figure 2: The five aspects of power system stability, from [1].

The following sections review these five stability aspects.

2.1.1 Classical power stability phenomena

Rotor angle stability

Rotor angle stability is defined as follows, [1]:

"Rotor angle stability is concerned with the ability of the interconnected synchronous machines in a power system to remain in synchronism under normal operating conditions and to regain synchronism after being subjected to a small or large disturbance."

Synchronous machines losing synchronism means that the rotor angles of some synchronous machines change (due to small or large disturbances) beyond a critical threshold beyond which the power system cannot settle to a stable equilibrium.

Assessing rotor angle stability requires simulating disturbances and monitoring the rotor angles of the synchronous machines with respect to each other. Rotor angle stability changes depend on the topology of the power system (e.g. which lines are in operation and how meshed the grid is). More specifically, the topology affects system damping which is a key factor to guarantee rotor angle stability.

Rotor angle stability also depends on the location and types of connected equipment such as synchronous machines, converter-interfaced generation, HVDC terminals, loads and so on.

Concerning the effects of current changes in power systems (more power electronics and converter-interfaced generation replacing synchronous generators), no general conclusion can be given as to their being beneficial or detrimental to rotor angle stability [1]. The effects are all case-specific.

Voltage stability

Voltage stability is defined as follows [1]:

"Voltage stability refers to the ability of a power system to maintain steady voltages close to nominal value at all buses in the system after being subjected to a disturbance."

Typically, voltage stability is concerned with decreases in voltage that trigger some protection systems, which may result in cascading failures. High voltages may also be a source of concern. The most severe consequence of poor voltage stability, in terms of societal impact, is voltage collapse resulting from too low voltages.

Monitoring voltage stability requires linear and nonlinear analyses of the operating conditions of interest. However, in practice, voltage intervals are defined in which power systems can be safely operated. Voltage instability may occur due to power transfers through corridors[1] increasing beyond the maximum transfer capability of the grid. Therefore, voltage stability can also be monitored by computing this maximum transfer capability and monitoring the power transfer through the corridors.

Frequency stability

Frequency stability is defined as follows [2]:

"Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load."

A sudden loss of generation (for example due to the sudden disconnection of a generator) or load (for example due to the sudden tripping of an exporting HVDC link) will impact the system frequency. Control systems are tuned and installed in the power system to contain frequency deviations from 50 Hz (in Europe) and eventually (after minutes) restore the frequency back to 50 Hz.

The response of the power system to such production / consumption imbalances depends both on an inherent response from connected equipment and on the response of tuned control systems. The inherent response depends on fundamental physics driving the active power load and generation as a function of system frequency.

[1] A corridor is a set of lines, commonly referred to as "cuts" in Sweden.

An example of inherent response is the inertial response of synchronous generators to a sudden loss of another synchronous generator. Following this loss, the remaining generators will see a larger active power load, which they will supply by extracting kinetic energy from their rotating rotor. The result will be a falling system frequency as the remaining generators slow down. The higher the inertia in the remaining generators the slower the frequency will decrease. This so-called inertial response is not due to any installed control systems. It is an inherent response from synchronous generators due to the physics at play.

Additional control systems are installed to stop this decrease in frequency (frequency containment reserves or FCR) and eventually to restore the system frequency to its nominal value (frequency restoration reserves or FRR). Converter-interfaced generation cannot contribute to the (inherent) inertial response. However, their power electronics can provide frequency response at least as fast as the control systems that equip synchronous generators [1]. Therefore, they can be used to provide FCR and FRR. They can also be used to provide fast-frequency responses (FFR), which is a type of frequency response faster than FCR (but slower than the inherent inertial response). When these fast-responding control systems are based on the rate of change of frequency of the system frequency (rather than on the frequency deviations as is the case for FFR), the resulting response is sometimes called virtual inertia since the corresponding controllers mimic the inherent inertial response from generators. This virtual inertial response is very fast but not as fast as the inherent instantaneous response of synchronous machines. Furthermore, it comes at the cost of additional control actions.

The displacement of synchronous generators by converter-interfaced generation results in lower system inertia. Lower system inertia results in (1) high rate-of-change-of-frequency (ROCOF) after a disturbance and (2) a larger frequency deviation after disturbances (lower frequency nadir below 50 Hz or higher frequency above 50 Hz). While ROCOF is not an issue in the Nordics, the lowest frequency nadir after dimensioning faults can result in unacceptable frequency with the current FCR [3]. This is why the Nordic countries have started procuring fast-frequency reserves for underfrequency which provides faster active power response than FCR.

Note that although converter-interfaced generation will contribute to even lower system inertia, situations with unacceptably low system inertia may already occur at low penetration rates of converter-interfaced generation, typically in the summer in the Nordics, when load is low, fewer synchronous generators are online and large nuclear power reactors are unavailable due to maintenance.

Thermal stability

In addition to rotor-angle, voltage and frequency stability, the term "thermal stability" is sometimes used to refer to keeping line currents under current ratings of equipment such as transmission lines, cables, and transformers [4]. Thermal stability is therefore concerned with avoiding thermal overloads. Thermal overloads (i.e. too high currents flowing in some equipment) may trigger protection systems, which will disconnect the overloaded pieces of equipment to protect it. The flow on these pieces of equipment will be re-distributed among the still intact part of the grid, which may overload additional equipment and lead to cascading failure.

2.1.2 New types of power system stability

In the revisited definition of power system stability [1], two new stability types have been included and defined: converter-driven stability and resonance stability, see below for definitions.

Both types of stability issues are of growing concern as the share of converter-interfaced equipment such as converter-interfaced generation, HVDC and FACTS devices increases in the power system. These new types of stability usually require time-demanding analyses. As of today, available data is too scarce to be able to build valuable indicators regarding these types of stability. Therefore, converter-driven and resonance stability will not be studied further in this report.

Converter-driven stability

Converter-driven instability can occur when interactions between the control systems of power electronics interact in an unstable way with the rest of the power system.

Resonance stability

Resonance stability is a particular type of small-signal stability that involves an oscillatory exchange of energy, due to interactions between different components in the power system. These interactions may in some cases be unstable in the sense that the created oscillations are undamped and will grow in size, possibly causing damage to equipment or unwanted disconnections.

An example of resonance instability is subsynchronous resonance (SSR) which is caused by unstable interactions between series-compensated lines and either the mechanical or electrical properties of generators. Interactions with mechanical properties of generators have been known and documented for a long time since they can occur in power systems with synchronous generators. Interactions with electrical properties of generators are somewhat new and have been documented in systems where doubly-fed induction generators (or DFIG, a kind of generator commonly used in wind turbines) have been interacting, sometimes in an unstable way, with series-compensated lines.

Resonance stability, and in particular SSR, is of concern in the Nordic power system with a higher share of DFIG and converter-interfaced generation [5], [6].

2.2 POWER SYSTEM STABILITY VS SECURITY

Power system security is closely related to power system stability. Power system security is defined as the ability of the power system to withstanding contingencies with acceptable new conditions. For the system to be secure, it needs to be and remain (1) stable and (2) within normal operating limits after pre-defined credible contingencies (so-called N-1 criterion). Normal operating limits are pre-defined thresholds for frequency, voltage and line currents (or line flows). Sometimes, thresholds on power transfer across corridors are also used to maintain rotor-angle and voltage stability.

Power systems stability before and after the pre-defined contingencies are necessary but not sufficient conditions of power system security. In addition to the stability criterion, the power system must remain within pre-defined normal operating intervals for voltage, frequency and line currents (or line flows).

To further define power system security, the concept of power system states was introduced in 1978 by Fink and Carlsen in [7]. These system states are still used today, up to a few adaptations and changes. Five power system states were defined in the original publication as illustrated in

Figure 3. The power system is said to be secure if it is in normal state.

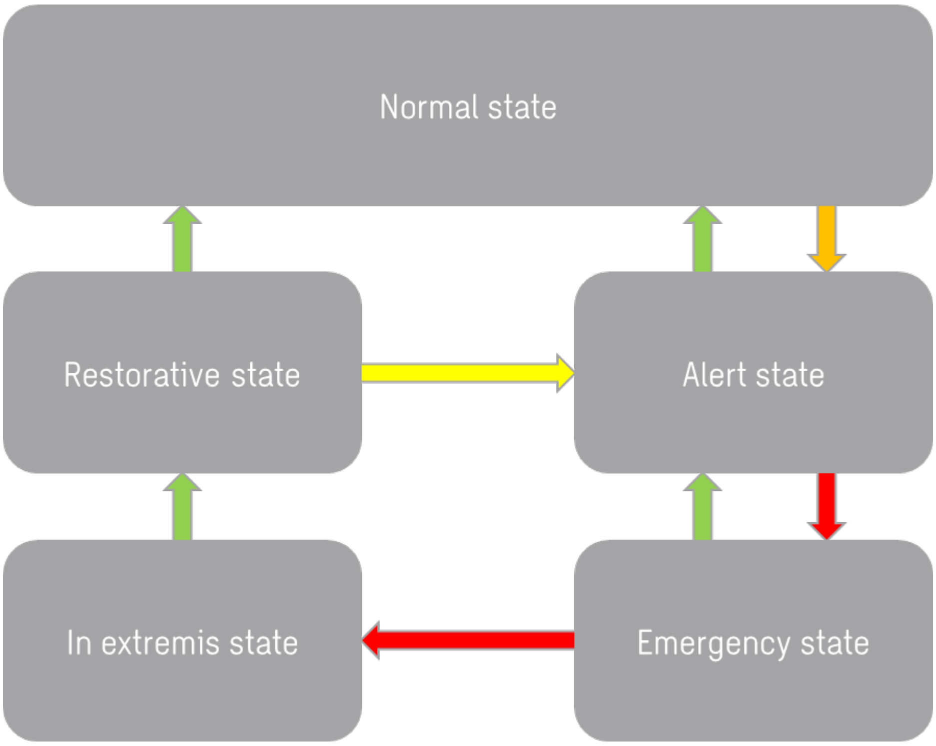

Figure 3: Power system states, as originally defined in [7].

The system states are defined as follows, where it is assumed that a set of credible contingencies has been defined.

- **Normal state**: The power system is in a normal state if it is stable and within operational security limits (voltage, frequency and line currents within pre-defined intervals) even after the occurrence of any single contingency in the set of credible contingencies.
- **Alert state**: The power system is in an alert state if it is stable and within operational security limits in the pre-contingency state, but at least one of contingencies in the credible set would lead to violation of operational security limits. For example, thermal overloads would occur after the occurrence of one of the contingencies. Here, operators can take *preventive actions* to bring back the power system to the normal state.

- **Emergency state**: The power system is in an emergency state if one of the operational security limits is violated. For example, the power system is experiencing thermal overloads. Here, operators need to take *corrective actions* to bring back the power system to the alert or normal state.
- **In extremis / blackout state**: The power system is in the in extremis state (or, in more recent version of the system states, in the blackout state) if it is experiencing instability issues, separation or cascading. Here, operators take *heroic actions* to maintain the integrity of the power system.
- **Restorative state**: The power system is in a restorative state if it has experienced partial or total blackout, or islanding, and *restorative actions* are being undertaken to restore it to the normal or alert state.

While dating back to 1978, this classification in 5 system states is still used today in grid codes to specify the responsibilities of system operators to maintain power system security, see for example the System Operations Guideline for Europe in Section 3.1.1 ([8]), the Emergency and Restoration Code [9] and the Reliability Guideline for Establishing Operating Limits in the US [10].

2.3 POWER QUALITY

Power quality is the degree to which electricity delivery is performed without disturbances or outages. More specifically, it can be defined as the degree to which the voltage, frequency, and waveform of a power supply system conform to established specifications.

Examples of disturbances that have an adverse effect on power quality are voltage transients, voltage dips, flickers and harmonics, see Figure 4.

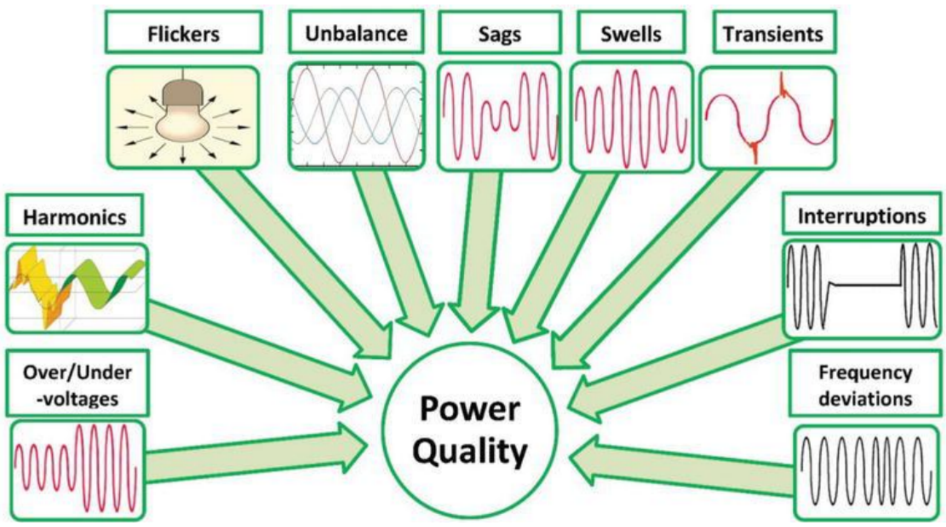

Figure 4: Examples of power quality aspects, from [11].

Figure 5 illustrates the relationships between power system security, power system stability and power quality.

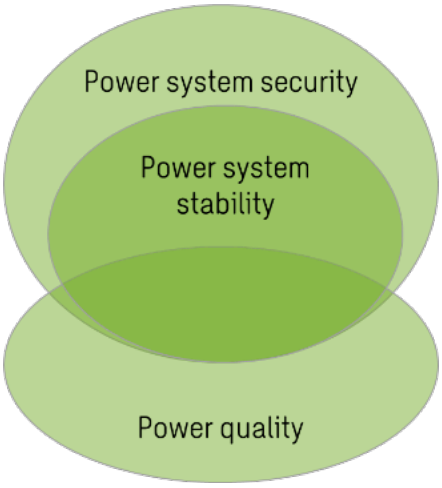

Figure 5: relationship between power system stability, power system security, and power quality.

As mentioned earlier, power system stability is a necessary but not sufficient condition for power system security: in addition of being stable to small and large disturbances, the power system needs to remain within pre-defined intervals for voltage, frequency, and line currents in order to be secure. These intervals are also part of the concept of power quality, which also includes other quantities not included in power system security (such as flickers).

Stability properties of the power system will have an impact on some quantities falling under power quality (voltage variations for example).

2.4 ADEQUACY, RELIABILITY, RESILIENCE

In addition to the concepts of power system stability, power system security and power quality, other concepts are also used to measure the degree to which the power system is able to adequately deliver electricity to the end-consumers.

Adequacy:
It is defined in [12] as "Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand or system operational constraints. These includes the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points".

Adequacy studies typically measure the frequency, magnitude and duration of power outage [13], that is the ability of the generation mix and the electricity grid to supply the load through the power systems, considering availability metrics of the different components. They result in indices such as expected energy not served (EENS) or loss of load probability (LOLP). In Europe, ENTSO-e regularly performs a pan-European Resource Adequacy Assessment (ERAA) according to a well-defined methodology [14]. For distributions systems, other common indices are System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI).

Reliability:
Reliability is divided into adequacy and security. Reliability has been defined in

slightly different ways by different entities. Reference [15] gives a recent review of the definitions of reliability and its sub-components, adequacy and security, in CIGRE, NERC, IEEE, IEC and ENTSO-e. The definition from ENTSO-e, for example, is “The degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired.” Therefore, power system reliability is assessed by doing adequacy studies and power system security assessments. Security of electricity supply is sometimes used instead of reliability [16].

A reliability standard will set a threshold of resource adequacy or power security indices. In Europe, for example, Article 25 of the Electricity Market Regulation [17] states that “A reliability standard shall indicate the necessary level of security of supply of the Member State in a transparent manner.” (Paragraph 1) and that “The reliability standard shall be calculated using at least the value of lost load and the cost of new entry over a given timeframe and shall be expressed as ‘expected energy not served’ and ‘loss of load expectation’.” (Paragraph 3). Therefore, the reliability standard relies on computing resource adequacy indices. In addition, the methodology approved by ACER[2] for computing these adequacy indices [18], the so-called European Resource Adequacy Assessment, states that network constraints should be considered, thereby also including power system security aspects into resource adequacy.

Figure 6 illustrates the relationships between the different elements of the reliability framework. Note that power quality has been included under reliability in this illustration due to its overlap with power system security.

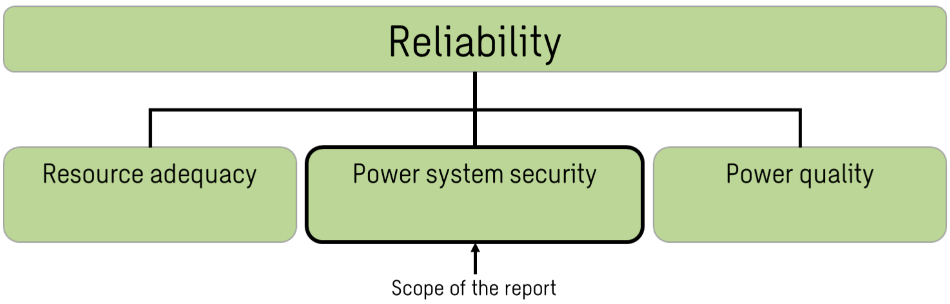

Figure 6: Relationship between resource adequacy, power system security, power system stability and power quality.

Resilience:
Several definitions of resilience in the context of electric power systems have been proposed [19]. There is not a single agreed-upon definition of resilience. Reference [15] reviews existing definitions and proposes the following definition “the ability to limit the extent, severity and duration of system degradation following an extreme event”, which is also the definition adopted by ENTSO-e in [20].

Important aspects of resilience are [21], [22], [15]:

- Robustness: the ability to absorb shocks and continue operating.

[2] European Union Agency for the Cooperation of Energy Regulators.

- Resourcefulness: the ability to skillfully manage a crisis as it unfolds.
- Rapid recovery: the ability to get services back as quickly as possible.
- Adaptability: the ability to incorporate lessons learned from past events to improve resilience.

Note that robustness is also a part of power system security, which studies the ability of power system to remain within pre-defined limits after credible contingencies. Robustness as part of resilience, however, captures the ability of the system to withstand extreme events.

Resilience emphasizes the system response to "extreme events", which usually are high-impact low-probability events such as cyber-attacks and external weather events. This is a major difference with the current definition of reliability and its two subcomponents power system security (which studies the system response to credible contingencies) and resource adequacy (which studies average indices such loss of load expectation) [23], [22].

In [15], different models linking resilience and reliability have been proposed with the one presented in Figure 7 being preferred, where resilience becomes a sub-property of reliability. This model recognizes that while resource adequacy captures average reliability levels and power system security captures the system's response to credible contingencies, reliability itself is not limited to credible events in its current definitions. Hence, extending it to extreme events by incorporating resilience into it makes sense and would make reliability a more encompassing property.

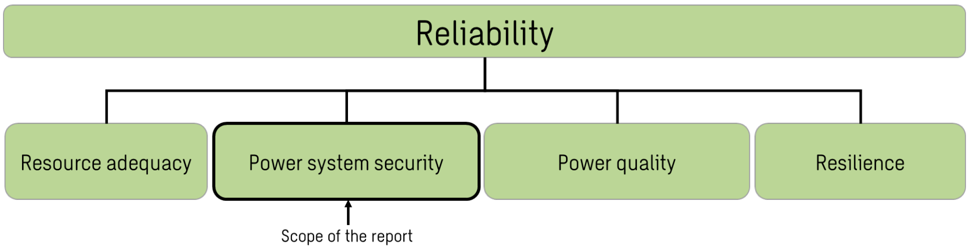

Figure 7: Proposed model linking resilience to reliability.

Frameworks for reliability studies, including resource adequacy assessments and power system security assessments, are rigorously defined in regulation in most countries and regions. In contrast, resilience is a rather new concept within the field of power system and has not been specified in regulation yet.

In the scope of this project, indicators for power system security will be explored. Indicators for the other aspects (resource adequacy, power quality quantities other than the ones related to power system security, and resilience) are left for future work.

Next chapter reviews European and national regulation related to power system reliability and, in particular, power system security. In addition, a review of existing indicators from regulatory texts is presented.

3 Regulations for power system security

Different layers of regulations exist when it comes to specifying criteria for power system security. In this chapter, the European, regional and national legislations relevant to power system security in the Nordic synchronous zone are reviewed. Furthermore, indicators related to power system security and disturbance statistics defined in the European regulations are reviewed.

3.1 EUROPEAN REGULATION

3.1.1 System operations guideline (SOGL) [8]

SOGL defines the responsibility of transmission system operators when it comes to power system security.

Among other things, it specifies the following important points:

- Definitions of the 5 system states (normal, alert, emergency, blackout and restoration states) which specify how power systems fulfil the security criteria.
- Operational security limits for voltage, currents and short-circuit current. In particular, voltage ranges for different voltage levels and regions are given.
- Frequency quality defining parameters and targets.
- The obligation of all TSOs in each synchronous area to analyse at least every two years the need of defining a minimum inertia threshold for frequency stability purposes.
- Annual reporting by the TSOs on some operational security indicators and indicators for frequency control.

SOGL is interesting for the present project because it defines formally the concepts of power system security (through the definition of system states) and specifies operational intervals and indicators that TSOs must monitor and report on.

3.1.2 Emergency and Restoration Code [9]

The Emergency and Restoration Code specifies how TSOs must act when the system ends up in the emergency, blackout and restoration states. In particular, it specifies that TSOs must design system defence plans to bring back the system from the emergency state to the normal state, and restoration plans to bring back the system from the emergency or blackout state to the normal state.

3.1.3 Connections guidelines

In the same way as SOGL defines the responsibility of transmission system operators when it comes to power system security, a series of connections guidelines (Requirements for Generators – RfG, Demand Connection Code – DCC and High Voltage Direct Current Connections – HVDC) specify the responsibility of connected equipment, among other things regarding fault-ride through capabilities.

3.1.4 Capacity Allocation & Congestion Management (CACM)

CACM specifies what cross-border capacity calculation should consider, in particular when it comes to power system security as defined in SOGL. It also specifies how thermal overloads should be handled (congestion management).

Because cross-border capacities consider power system security as specified in CACM, they can be used as proxy indicators for some of the operational security indicators defined in SOGL.

3.2 REGIONAL LEGAL FRAMEWORK

As a complement to the European regulation, some regional regulations or proposals apply, common to several countries (usually all countries within a synchronous area). In many cases, these legal texts build on top of the European regulation and specify it in more detail for their corresponding regional settings. Examples are:

- "Nordic synchronous area proposal for the frequency quality defining parameters and the frequency quality target parameter" [24]. This is an implementation of Article 127 of SOGL for the Nordic countries and gives the value of the frequency quality defining parameters, see Table 1. In addition, it states that the maximum number of minutes outside the standard frequency range for the Nordic synchronous area is 15,000 minutes per year, but that the aim is for it to be under 10,000 minutes per year.
- "Requirement for minimum inertia in the Nordic power system" [25]. This reports on a Nordic analysis on (1) the tools available to ensure that the minimum frequency nadir after the largest dimensioning fault remains above 49 Hz (below which large amount of load shedding will occur) and (2) whether a minimum inertia level must be implemented in the Nordics. The report concludes that there is no such need, because it is more cost efficient to procure fast-frequency reserves (FFR) or, as a last resort, to limit the size of the dimensioning fault (by curtailing the dimensioning generators or limiting large imports from HVDC links).

Table 1: Frequency quality defining parameters in the Nordics [24].

nominal frequency	50Hz
standard frequency range	±100 mHz
maximum instantaneous frequency deviation	1000 mHz
maximum steady-state frequency deviation	500 mHz
time to restore frequency	15 minutes
frequency restoration range	±100 mHz
alert state trigger time	5 minutes

3.3 NATIONAL LEGISLATION

Finally, national legislation complements both European and regional legislation either by specifying national values for some parameters defined in European / regional legislation or by specifying new legal responsibilities. Examples are:

- National electricity legislation which, among other things, translate the European legislation into national legislation.
- Energimarknadsinspektionen's regulation on the establishment of general requirements for generators [26], which specifies, for example, specific voltage and frequency thresholds for Sweden that different types of generators must be able to ride through without disconnecting. It therefore includes the implementation of RfG in a Swedish context. It also includes other provisions based on Swedish laws and therefore goes beyond RfG.
- National technical guidelines for power quality defining thresholds for quantities related to power quality, see for example [27].

3.4 INDICATORS DEFINED IN EUROPEAN REGULATION

There are existing indicators related to power system security and robustness. In particular, ENTSO-e has been developing an Incident Classification Scale (ICS) methodology that define categories of incidents and indicators related to power system security since 2012. Corresponding reports collecting the values of these indicators for different regions in Europe have been published annually since 2013.

The ICS methodology has been updated multiple times, the last time in 2019. As stated in the ICS reports: "The update has significantly changed the reported data. Therefore, the results gathered after each update cannot be directly compared to those from previous years." Therefore, the ICS indicators cannot be used to capture trends in power system security.

In addition to the ICS work, ENTSO-e and other regional organizations before it has also collected disturbance statistics. The current methodology is a result of multiple updates of the original common rules defined in Nordel in 1964. Nordel was the organization of the Nordic TSOs. It was ended in 2009 when its activities were transferred to being carried out within ENTSO-e instead. The latest update of the methodology dates from 2021 [28]. The disturbance indicators collected in the disturbance statistics therefore suffer from the same shortcoming as the ICS, i.e. the difficulty to capture trends over time due to changes in the methodology.

Still, the ICS and disturbance indicators may be relevant to follow up in the future once the methodologies have been stabilized. Therefore, they are reviewed below.

3.4.1 Incident Classification Scale

ENTSO-e has developed an Incident Classification Scale (ICS) methodology [29] which defines (1) a scale from 0 to 3 for different categories of incident related to power system security and (2) a set of operational security indicators based on the ICS. The scales relate to the system state definitions, see Section 2.2 and Table 2

Scale	System state	Definition
"Below scale"	Normal state	Anomalies and local events
Scale 0 "Noteworthy"	Normal state	Local events
Scale 1 "Significant incident"	Alert state	Significant incidents with violation of operating security limits
Scale 2 "Extensive incident"	Emergency state	Extensive incidents involving probability of wide area incident
Scale 3 "Major incident"	Blackout state	Major incidents in the control area of a single TSO

Table 2: Definition of the scales in the ICS methodology.

The categories of incidents are blackouts (OB3), on loads (L), network elements (T), power generation facilities (G), leading to frequency deviations (F), N or N-1 violations (N), separation from the grid (RS), loss of tools, means and facilities (LT), violation of standards on voltage (OV), and reduction of reserve capacity (RRC).

The latest ICS definition combining scale and category of incident is given in Figure 8. The TSOs must report incidents falling into these categories at the latest by the end of the month following the month in which the incident began.

Below scale Anomaly		Scale 0 Noteworthy		Scale 1 Significant incident		Scale 2 Extensive incident		Scale 3 Major incident	
Priority	Short definition (Criterion short code)	Priority	Short definition (Criterion short code)	Priority	Short definition (Criterion short code)	Priority	Short definition (Criterion short code)	Priority	Short definition (Criterion short code)
		#20	Incidents on load (L0)	#11	Incidents on load (L1)	#2	Incidents on load (L2)	#1	Blackout (OB3)
#28	Incidents leading to frequency degradation (FBS)	#21	Incidents leading to frequency degradation (F0)	#12	Incidents leading to frequency degradation (F1)	#3	Incidents leading to frequency degradation (F2)		
		#22	Incidents on network elements (T0)	#13	Incidents on network elements (T1)	#4	Incidents on network elements (T2)		
#29	Incidents on power generating facilities (GBS)	#23	Incidents on power generating facilities (G0)	#14	Incidents on power generating facilities (G1)	#5	Incidents on power generating facilities (G2)		
				#15	N-1 violation (ON1)	#6	N violation (ON2)		
		#24	Separation from the grid (RS0)	#16	Separation from the grid (RS1)	#7	Separation from the grid (RS2)		
#30	Violation of standards on voltage (OVBS)	#25	Violation of standards on voltage (OV0)	#17	Violation of standards on voltage (OV1)	#8	Violation of standards on voltage (OV2)		
		#26	Reduction of reserve capacity (RRC0)	#18	Reduction of reserve capacity (RRC1)	#9	Reduction of reserve capacity (RRC2)		
		#27	Loss of tools, means and facilities (LT0)	#19	Loss of tools, means and facilities (LT1)	#10	Loss of tools, means and facilities (LT2)		

Figure 8: Latest Incident Classification Scale (ICS), from [30].

From the number of reporting incidents, the ICS methodology also defines a number of operational security indicators relevant for operational security (OS) and operational planning (OPS). These indicators are aggregates of the number of incidents across several incident scales (usually sum of the number of incidents on scale 0 to 3). These indicators are given in Table 3.

Table 3: Definition of operational security indicators, from [29].

Abbreviation	OS-A	OS-B	OS-C	OS-D1
Name of the indicator	Number of tripped transmission system elements	Number of tripped power generation facilities	Energy not supplied due to unscheduled disconnection of demand facilities	Time duration of being in alert and emergency states
Abbreviation	OS-D2	OS-E1	OS-E2	OS-F1
Name of the indicator	Number of instances of being in alert and emergency states	Time duration within which there was a lack of reserve identified	Number of events within which there was a lack of reserve identified	Time duration of voltage deviations exceeding the ranges from tables 1 and 2 of SO GL
Abbreviation	OS-F2	OS-G1	OS-G2	OS-H
Name of the indicator	Number of voltage deviations exceeding the ranges from SOGL	Number of minutes outside the standard frequency range	Number of minutes outside the 50% of maximum steady state frequency deviation	Number of system-split separations of local blackout states
Abbreviation	OS-I	OPS-A	OPS-B	OPS-C
Name of the indicator	Number of blackouts involving two or more TSOs	Number of events in which an incident contained in the contingency list led to a degradation of the system operation state	Number of events counted by OPS-A in due to unexpected discrepancies from load or generation forecasts	Number of events in which there was a degradation of system operation conditions due to an exceptional contingency
Abbreviation	OPS-D	OPS-E		
Name of the indicator	Number of events counted by OPS-D due to unexpected discrepancies from load and generation forecasts	Number of events leading to a degradation in system operation conditions due to lack of active power reserve		

3.4.2 Nordic and Baltic Grid Disturbance Statistics

ENTSO-e has defined a pan-European methodology [28] for collecting disturbance statistics. It was last updated in 2021.

Among other things, the methodology defines faults and grid disturbances as

- Faults: "Inability to perform as required, due to an internal state"
- Grid disturbances: "Automatic, unintended, or manual undeferrable outages of breakers as a result of faults in the power grid."

While disturbance statistics are partly included in the ICS report, the statistics in the Grid Disturbance Statistics dig deeper into faults, grid disturbances and resulting energy not served, down to individual component level. In particular, statistics about the causes of faults and grid disturbances are given.

The latest Nordic and Baltic Grid Disturbance Statistics report can be found in [31].

4 Framework for grid indicators

In this chapter, the framework and guiding principles developed in this project for power system robustness indicators are presented in Section 4.1. They are applied to frequency and voltage quality in Sections 4.2 and 4.3, respectively.

4.1 GUIDING PRINCIPLES FOR SELECTING INDICATORS

One way to understand the operation of a grid is to think of it in terms of preconditions, unplanned events, measures taken and resulting outcomes for a system parameter. Displayed as an equation, one might think of it like this:

Preconditions + unplanned events + measures taken = resulting outcome

As an example, a *resulting outcome* might be the average value of the system frequency for a given time, which one would like to keep within a defined range (near nominal frequency). One of the *preconditions* for this task is the amount of production with frequency control modes. *Unplanned events* might then be disconnection of production units due to faults, and *measures taken* could for instance be to activate one or more reserves.

A basic strategy that has been applied in this study, when it comes to deciding on grid indicators, is to choose indicators that say something about either of the four categories above. In other words, the proposed indicators all illustrate some aspect of preconditions, unplanned events, measures taken or a resulting outcome.

In addition to this, the following principles have been applied to find relevant indicators:

- Rather than designing an indicator which combines several aspects of grid stability, a group of indicators has been chosen. This choice was made to easier distinguish the different aspects that are relevant.
- Keep the number of indicators limited (5–10), with the aim to make it possible to study them all as a group and to be able to have a good overview of them all.
- Make the indicators as simple as possible. The aim has been to have indicators which are possible to understand without a deep knowledge of how the grid works.
- Design indicators based on data which is available today, or data which could in theory be made available with a limited amount of work.
- Choose indicators which can be illustrated numerically.
- Design the indicators so that the interpretation of their increase/decrease is unambiguous, all other things equal. In other words, for each indicator, it should be clear if an increase is an improvement or an impairment in terms of stability, if nothing else has changed in the system.
- The selection of indicators has not been limited to quantities which have a clear target value. A target value could be a benefit for an indicator, but there could also be cases where interpreting general trends is relevant.

- After discussions with stakeholders, the scope for the indicators has been limited to indicators with a time resolution of hours – years have been chosen. This is to capture longer trends in power systems. Changes that are faster than this time resolution, such as dynamic excursions on a second or minute basis, have been aggregated to hourly, monthly or yearly indicators.

4.2 APPLICATION TO FREQUENCY

In this section, indicators to assess frequency stability and quality are proposed. Frequency is a global quantity common to a whole synchronous area. The indicators designed in this section are therefore quantities for a whole synchronous area. The indicators were computed for the whole Nordic synchronous area in Section 4.2.2.

Note that there exist other reports reporting on the frequency quality in the Nordics. An example of this is the yearly report by the Finnish system operator, the latest version of which is available in [32]. This report focuses on a detailed analysis of the system frequency, i.e. the "outcome". In contrast, the indicators presented below capture a wider scope in addition to the outcome (preconditions, unplanned events and measures taken) and have been designed to be as simple as possible.

4.2.1 List of indicators for frequency quality

The equation given in Section 4.1 is applied to the case of frequency quality to develop meaningful indicators.

Preconditions + unplanned events + measures taken = resulting outcome

For frequency quality, the following indicators were selected. More detail about these indicators, as well as additional indicators that were considered but eventually not selected, is given farther down.

- For measuring the *outcome*:
  - **Indicator 1 and 2**: Min / max value of frequency, per month.
  - **Indicator 3**: Number of minutes outside the interval for normal state for frequency, per month.
- For measuring the *preconditions*:
  - **Indicator 4**: Monthly average kinetic energy.
  - **Indicator 5**: Rolling 12-month average of the kinetic energy.
- For measuring *Unplanned events*:
  - **Indicator 6**: Total monthly imbalance volumes in the synchronous area.
- For measuring the *measures taken*:
  - **Indicator 7**: Sum of activated frequency regulation reserve

Table 4 gives the list of the indicators that have been considered in the scope of this project to measure the outcome (frequency quality), and whether or not they were finally selected. Out of these indicators a few have been selected to give an adequate overview of frequency quality, according to the principle of having as few indicators as possible.

Different indicators can be computed from a historical time series of the system frequency. Some of them capture normal conditions and some of them capture extreme events. Normal conditions are for example captured by average values while more extreme events are captured by min and max values and extreme quantiles. It is important to get both types to have an overview of frequency quality that is as complete as possible. This will be illustrated in Section 4.2.2.

Table 4: List of indicators considered for the outcome (frequency quality).

Indicator name	Unit	Computation	Selected or not, and why.
Number of minutes outside the interval for normal state for frequency	Minutes	In the Nordics, the interval for normal state for frequency is [49.9 Hz ; 50.1 Hz]. Counting the number of minutes outside this interval depends on the sampling rate of available data and definitions of how long deviations must be.	**Selected**. This indicator has determined target values in most synchronous areas. It is simple to interpret: the more minutes outside the normal interval, the worse the frequency quality.
Portion of time within the normal interval	%	Computed from the previous indicator as the ratio between the number of minutes inside the normal interval by the total number of minutes in the chosen time period (typically month or year)	**Not selected.** It captures the same information as the number of minutes outside the normal interval but does not have pre-determined target value.
Min / max value of frequency	Hz	Min and max values are computed from historical time series of the system frequency for a pre-defined time resolution, for	**Selected.** This data complements the number of minutes outside the normal interval by capturing extreme frequency

Indicator name	Unit	Computation	Selected or not, and why.
		example monthly values. The result depends on the sampling rate of the time series.	deviations. It is easy to interpret: the larger the max (or lower the min), the more severe the consequences of the event was leading to these values.
Average value of frequency	Hz	Computed from historical time series for the system frequency as the average for a pre-defined time resolution.	**Not selected.** The average value of the frequency on the time periods of interest (hours / month / years) is almost always 50 Hz. Hence, the indicator does not convey any meaningful information.
Average value of frequency, when outside normal interval	Hz	Computed from historical time series for the system frequency as the average for a pre-defined time resolution.	**Not selected.** It could complement the min and max value of the frequency to measure how serious frequency deviations were outside of the normal interval. However, to keep the number of indicators as low as possible, it was excluded.
Extreme quantile of frequency	Hz	Computed from historical time series for the system frequency as the average for a pre-defined time resolution. Typical extreme quantiles would be 95% or 99% quantiles.	**Not selected.** Deviations of the frequency outside of the normal interval are rare events. Hence, even an extreme quantile like the 99%-quantile is very often within the normal interval. Therefore, this

Indicator name	Unit	Computation	Selected or not, and why.
			indicator does not convey any meaningful information.
Min and max values of the time error per week	Seconds	The time error captures the accumulated difference between a clock running at the system frequency and a reference clock. The longer the frequency remains away from 50 Hz, the larger the time error. It can be computed by integrating the difference between these two clocks using historical time series for the frequency.	**Not selected.** The time error is difficult to interpret. It does not provide any additional and easy-to-interpret information than the other selected indicators.

Table 5 gives the list of the indicators that have been considered in the scope of this project to measure preconditions. Both indicators capture the amount of kinetic energy available in the power system. Everything being equal, an increase in kinetic energy will lead to smaller frequency deviations. The monthly mean allows to capture seasonal variations while the rolling 12-month average filters out most of these variations and allows for the identification of long-term trends.

Table 5: List of indicators for preconditions.

Indicator name	Unit	Computation	Selected or not, and why.
Monthly mean of kinetic energy	GWs	Computed from a historical time series of the kinetic energy.	**Selected.** The data is available and it conveys easy-to-interpret information: the less kinetic energy, the more difficult it is to achieve good frequency quality, everything else being equal.
Rolling 12-month average of the kinetic energy	GWs	Computed from a historical time series of the kinetic energy.	**Selected.** This indicator is somewhat overlapping the previous one. It was deemed to provide valuable additional information, by filtering out variations and giving a clearer picture of the trend in the kinetic energy.

Table 6 lists indicators capturing unplanned events in the context of frequency quality. They are both based on imbalance volumes. Imbalances are computed per balance responsible party in the settlement process as the difference between the produced (or consumed) energy per hour and the planned production (or consumption) according to all trades on both day-ahead and intraday markets. Everything else being equal, a large imbalance volume will lead to larger frequency deviations.

Table 6: List of indicators for unplanned events.

Indicator name	Unit	Computation	Selected or not, and why.
Total monthly imbalance volumes in the synchronous area	MWh	Computed from a historical time series of the imbalance data.	**Selected.** It is an easy-to-interpret indicator: the larger the imbalances the larger the frequency deviations, everything else being equal.
Extreme quantiles of the hourly imbalance volumes	GWs	Computed from a historical time series of the kinetic energy. It captures the largest imbalances observed during one hour in a specified period.	**Not selected.** While this indicator has in theory the ability to complement the previous one, it was seen in the analysis of this project that they both exhibit the same trends. Therefore, it becomes superfluous.

Table 7 lists indicators capturing the measures taken to ensure an adequate frequency quality. They are related to volumes and procured frequency regulation reserves. The extreme quantiles capture the largest amounts of procured or activated reserves, which quantify extreme situations.

Table 7: List of indicators for measures taken.

Indicator name	Unit	Computation	Selected or not, and why.
Sum of activated frequency regulation reserve	MWh	Computed from historical time series from settlement data.	**Selected.** Activated volumes are easy-to-interpret: the more activated volumes, the more "effort" was required to maintain an adequate frequency quality.
Sum of procured frequency regulation reserve	MWh	Computed from historical time series from settlement data.	**Not selected.** Procured volumes could complement activated volumes by showing the level of readiness. However, to keep the number of indicators as low as possible, it was decided to omit it and keep activated volumes instead.
Extreme quantiles of hourly activated frequency regulation reserve	MWh	Computed from historical time series from settlement data.	**Not selected.** For similar reasons as for imbalance volumes, extreme quantiles have not been selected. Analyses have shown that they convey exhibit similar trends as the sum of volumes.
Extreme quantiles of hourly procured frequency regulation reserve	MWh	Computed from historical time series from settlement data.	**Not selected.** For the same reason as the quantiles of activated volumes.

4.2.2 Visualisation of the indicators

The figures below visualize the selected indicators computed for the Nordic synchronous area:

- For measuring the *outcome*:
  - Figure 9**:** Min / max value of frequency, per month (**Indicators 1 and 2).**
  - Figure 10**:** Number of minutes outside the interval for normal state for frequency, per month (**Indicator 3**).
- For measuring the *preconditions,* Figure 11:
  - Monthly average kinetic energy (**Indicator 4**)
  - Rolling 12-month average of the kinetic energy (**Indicator 5**)
- For measuring *Unplanned events*:
  - Figure 12**:** Total monthly imbalance volumes in the synchronous area (**Indicator 6**).
- For measuring the *measures taken*:
  - Figure 13**:** Sum of activated frequency regulation reserve (**Indicator 7**).

The scope of the present report is to design indicators that are meaningful to measure the robustness of power systems. It is not to provide a complete analysis of this robustness. However, a few trends from the selected indicators are analysed below.

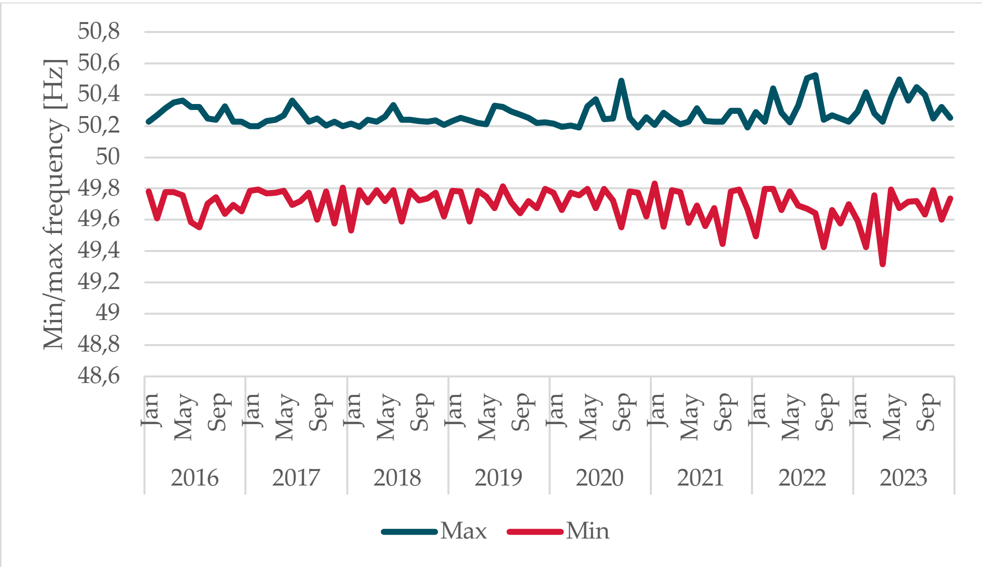

Figure 9: Monthly min and max system frequency, [33].

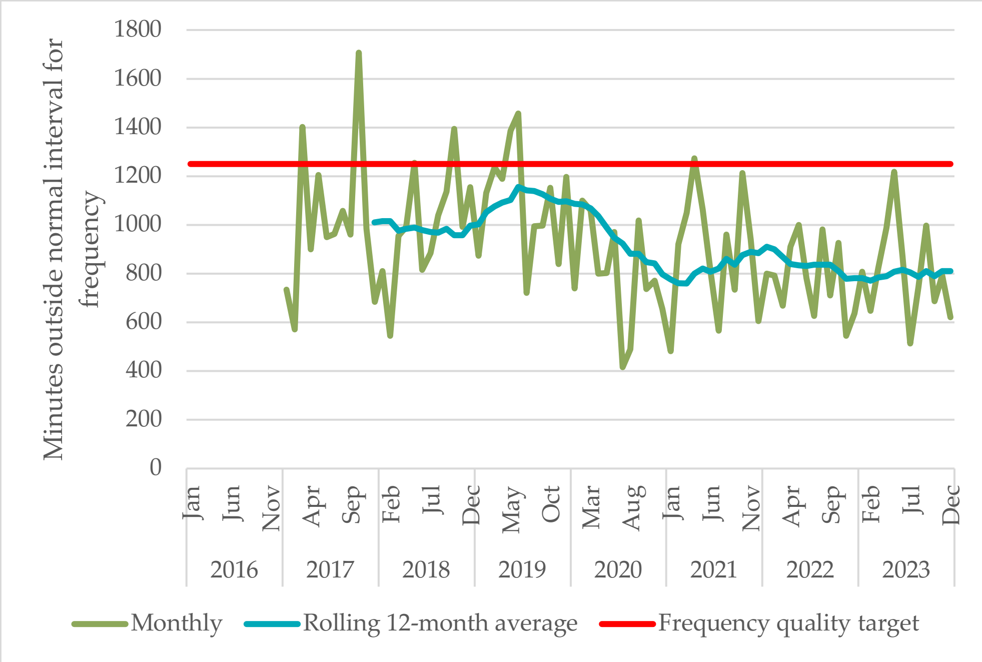

Figure 10: Number of minutes per month outside the normal interval [49.9Hz,50.1Hz] for frequency, from ENTSO-E's Load Frequency Control reports (see the latest at [34]).

The indicators in Figure 9 and Figure 10 relate to the outcome, i.e. to the frequency quality.

The min and max frequency for each month show an increasing trend since the beginning of 2021. Factors that may have contributed to the increase in events leading to larger frequency deviations are the start of operation for two new HVDC cables (North Sea Link from Norway to Great Britain and Nordlink from Norway to Germany) and one new nuclear power plant (Olkiluoto 3 in Finland). Another factor may be the decrease in system inertia as seen in Figure 11.

Looking at the number of minutes outside the normal interval for frequency, the picture looks different. This indicator shows a decreasing trend since 2019, with a slight increase in 2021, before decreasing again in 2022 and stabilizing in 2023. Therefore, the frequency quality measured from this indicator has become better in the past year. Identifying all factors contributing to this are complex. One of the factors is the increasing amount of activated frequency reserves, the indicator in Figure 13.

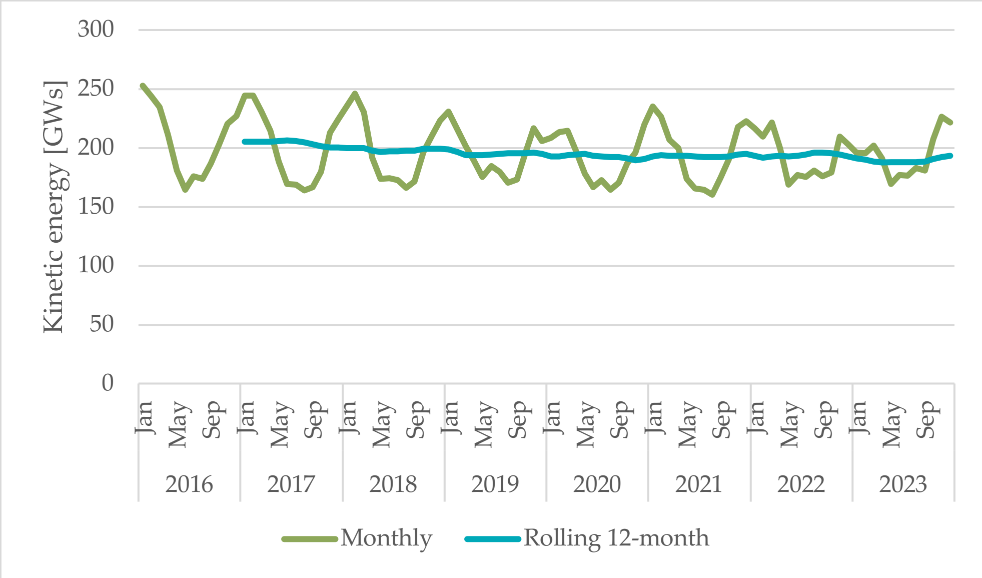

Figure 11: Monthly mean of kinetic energy, from [33].

Figure 11 shows both the monthly average kinetic energy in the Nordic synchronous area (what is usually called "system inertia") and its one-year rolling average. The rolling average clearly shows a long-term decreasing trend from above 205 GWs in the beginning of 2017 to around 190 GWs in 2023. The monthly average shows the seasonal variation: a larger amount of kinetic energy in the winter when more synchronous generators are online and a smaller amount in the summer when the load is lower and fewer synchronous generators are online (the summer is for example the revision period for nuclear reactors). The seasonal variation also shows more detail about the decrease in system inertia in winter and summer. In the winter 2016/2017, the maximal system inertia was 245 GWs. This decreased to 210 GWs for the winter 2022/2023, a larger decrease than the one captured by the rolling average. In contrast, there is no noticeable decrease of system inertia in the summer months. It has varied between 165 and 170 GWs, with summers 2019 and 2023 having the highest levels of system inertia.

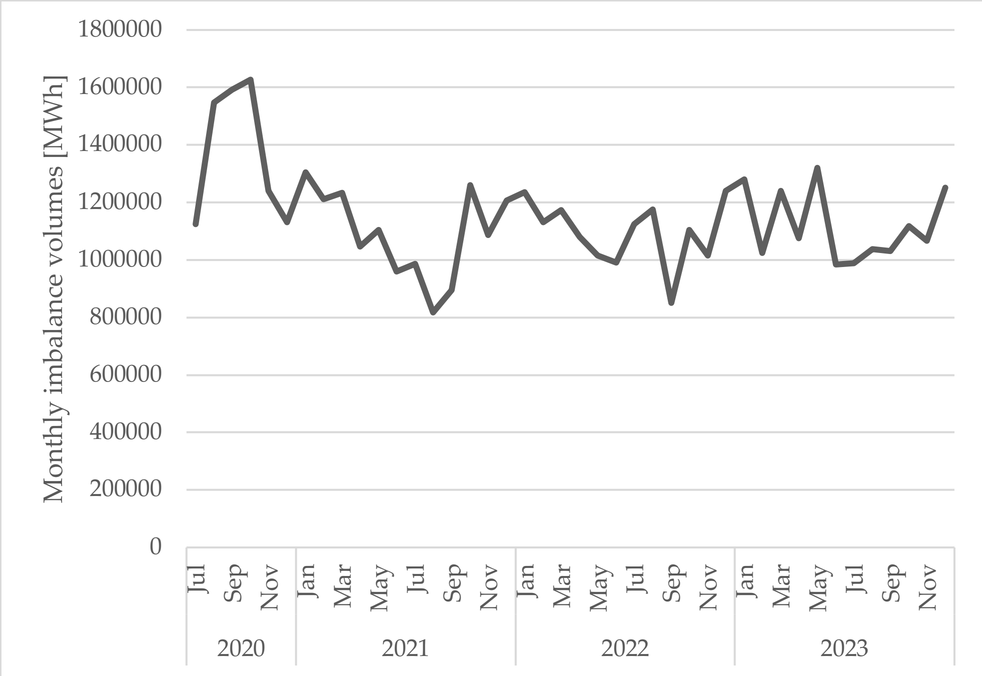

Figure 12: Monthly absolute imbalance volumes (sum of absolute hourly imbalance volumes), from ENTSO-E Transparency Platform.

Figure 12 shows the total monthly absolute imbalance volumes. Imbalance volumes are the difference between what actors plan to produce (or consume) and what they actually produce (or consume). The plans are set by trades on the day-ahead and intraday markets. These imbalances, everything else being equal, result in frequency deviations that must be handled by the system operators. This indicator shows a decrease in imbalance volumes from 2020 to 2021, after which it has stabilized. It is outside the scope of this report to do a complete analysis of the contributing factors. Some factors that may have contributed are new installed capacity, the change in the imbalance settlement from a two-price to one-price system at the end of 2021 [35], the change from a one-hour to a 15-minute imbalance settlement period in May 2023 [36][3] as well as the annual updates in imbalance fees.

[3] 15-minute trading periods on the day-ahead and intraday markets will be introduced later in 2025.

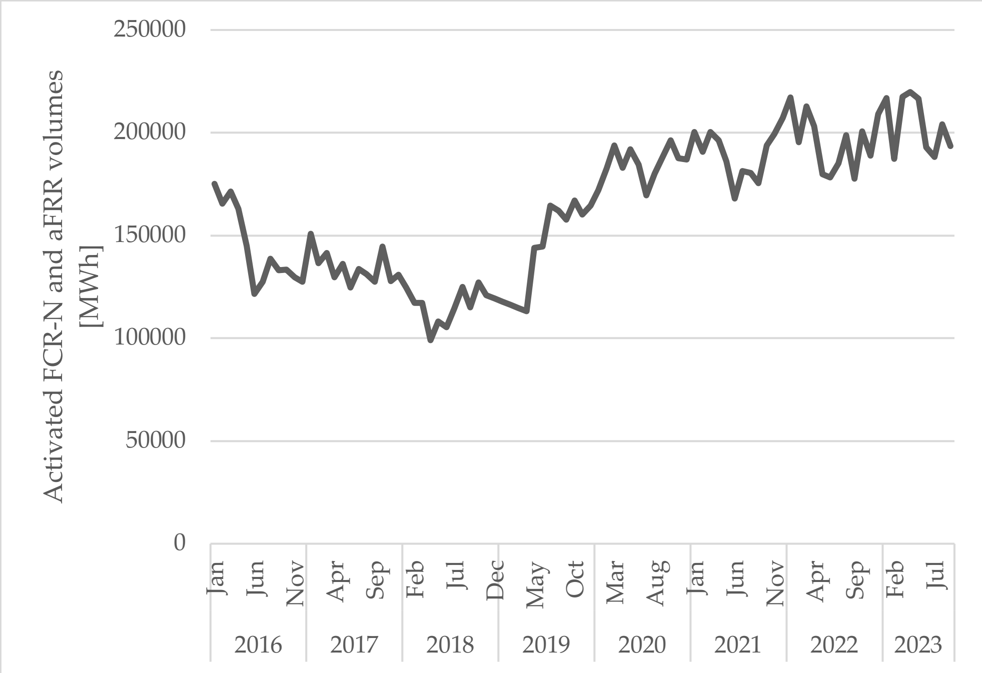

Figure 13: Monthly volumes of activated FCR-N and aFRR, from ENTSO-E's Transparency Platform.

Figure 13 shows the total monthly volumes of activated FCR-N and aFRR, both up and down, in the Nordic synchronous area. It has been chosen to exclude the volumes of mFRR because mFRR bids can be activated for congestion management purposes (in addition to being used for frequency regulation). The indicator shows a clear increasing trend in activated volume from 2019. Although the indicator does not show it, analysis of the underlying data reveals that increase volumes of aFRR started to be activating in 2019. This was an intentional strategy from the TSOs to increase frequency quality. It was already seen from the indicator on the number of minutes outside the normal interval for frequency (Figure 10) that this strategy has had a beneficial effect and improved frequency quality.

4.3 APPLICATION TO VOLTAGE

In this section, indicators to assess voltage stability and quality are evaluated and proposed. Whereas frequency quality is a well-established concept, voltage stability and quality are not as precisely defined. For example, voltage stability may refer to avoiding voltage collapse or to keeping large enough margins by keeping voltages within standard intervals for normal operations. The latter may also be understood as part of voltage quality. In this section, voltage stability and quality are used interchangeably to refer to keeping voltages within standard intervals for normal operations.

Unlike frequency, voltage is a local parameter which will impact the conditions when evaluating status of the power system. Hence, measuring voltage profile in a single point will not give a proper indication for estimating voltage stability in more distant areas of the power system. However, the project group finds it beneficial to have indicators for voltage on both local and global level, since local indicators will give detailed information of a specific connection point in the power system and global indicators will facilitate the ability to make an overall analysis of voltage quality. But even though the global indicators are addressed on a broader level compared to local voltage indicators, the global perspective must be applied on delimited areas and not on areas for example in size of the synchronous area. How proper voltage areas should be defined is not examined in this project, it has to be further analysed when using global indicators. Therefore, the evaluated indicators in this section are divided into local and global indicators to separate the different characteristics and purpose.

4.3.1 List of indicators related to voltage stability and quality

Several indicators related to evaluation of voltage deviations are presented, since stable voltage is a prerequisite for efficient and safe functionality of the power system.

Depending on specific voltage level in the power system to be assessed, different voltage intervals for evaluation have to be assumed. For example, when visualizing the proposed voltage indicators in this report, measurement for a 400 kV node in the Swedish transmission system is evaluated within the interval of 400-415 kV. The indicators for voltage deviation could be evaluated both on a local and global level.

Additionally, an indicator for short circuit power is evaluated since it provides an indication of inherent ability of the power system to counteract voltage deviations. Also, an indicator visualizing the number of shunt element maneuvers is listed below because it could give an indication of how much voltage is fluctuating in a specific node or area. This indicator could be evaluated both on a local and global level.

Regarding additional global voltage indicators which are evaluated for a broader but delimited area, the amount of available inductive and capacitive reserves and the amount of time with lack of available inductive and/or capacitive reserves gives an indication of the ability to handle voltage deviations in the power system.

The indicator which provides number of nodes with more than X minutes outside recommended voltage interval, gives an indication of propagation of voltage deviations within an area. Hence, it gives additional information of voltage stability which could be beneficial to used together with other indicators when analyzing grid robustness.

The total number of evaluated voltage indicators in this project are presented in Table 8.

Table 8. List of presented voltage indicators.

Name indicator	Local	Global	Unit	Computation	Evaluation
Number of minutes outside recommended voltage interval	x		minutes	Computed from the number of minutes outside of the recommended interval. The voltage interval to	Monthly or yearly

Name indicator	Local	Global	Unit	Computation	Evaluation
				be applied is dependent on where voltage is measured. For computation of global indicator total number of minutes outside recommended voltage interval for all nodes within an area are aggregated. The indicator is computed individually for both high and low voltage.	
Maximum/minimum voltage	x		kV	The indicator is calculated individually for both high and low voltage.	Hourly
Median voltage outside recommended voltage interval	x		kV	The voltage interval to be applied is dependent on where voltage is measured. The indicator is computed individually for both high and low voltage.	Hourly
Minimum short circuit power	x		MVA	Computed individually for every node.	Yearly or when significant changes in grid topology is done.
Number of shunt manoeuvres	x	x	Number	Computed individually for every entity. For computation of global indicator total number of manoeuvres within an area are aggregated.	Daily

Name indicator	Local	Global	Unit	Computation	Evaluation
Amount of available inductive and capacitive reserves		x	Mvar	Aggregation of reactive reserves within an area. Computed for both inductive and capacitive reserves divided into static and dynamic reserves.	Hourly
Amount of time with lack of available inductive and/or capacitive reserves		x	Hours	Aggregation of time during which there was a lack of inductive/capacitive reserves within an area. Computed for both static and dynamic inductive and/or capacitive reserves.	Hourly
Number of nodes with more than X minutes outside recommended voltage interval		x	Number	Aggregated number of nodes within an area. The indicator is calculated individually for both high and low voltage. Suitable number of X is to be defined.	Monthly or yearly

4.3.2 List of selected indicators related to voltage

The equation given in Section 4.1 is applied to the case of voltage stability and voltage quality to select meaningful indicators.

Preconditions + unplanned events + measures taken = resulting outcome

From the list given in Table 8, four voltage indicators have been selected for further use. Two of them are for local use and two of them are for global use. More detail about the selected voltage indicators and reasons for selection are given in Table 9.

- For measuring the *outcome*:
  - **Indicator 1**: Number of minutes outside recommended voltage interval, per month or year.
  - **Indicator 2**: Maximum/minimum voltage, per hour.
  - **Indicator 4**: Number of nodes with more than X minutes outside recommended voltage interval, per month or year.

- For measuring the *preconditions*:
    - **Indicator 3**: Amount of available inductive and capacitive reserves, per hour.

However, the other indicators that were considered but eventually not selected contribute to evaluate grid robustness, but the indicator may not contribute significantly to already achieved information. Additionally, results of the indicators could be ambiguous, or data could be difficult to access and therefore it could be difficult to calculate and use the indicator. Voltage indicators that were considered but eventually not selected, are given in Table 10.

Table 9. List of indicators selected and motivation.

Indicators selected			
Name indicator	**Local**	**Global**	**Motivation**
Number of minutes outside recommended voltage interval	x		The indicator is easy to calculate and easy to understand. The indicator gives a good indication of voltage quality and stability.
Maximum/minimum voltage	x		The indicator is easy to calculate and easy to understand. The indicator gives a good indication of voltage quality and stability.
Amount of available inductive and capacitive reserves		x	It could be difficult to find data to calculating the indicator, but it gives additional information about ability to handle voltage deviations.
Number of nodes with more than X minutes outside recommended voltage interval		x	The indicator is easy to calculate and aggregate, it is also easy to understand. The indicator gives an overall indication of voltage quality and stability in a broader area.

Table 10 List of indicators not selected and motivation.

Indicators not selected			
Name indicator	Local	Global	Motivation
Median voltage outside recommended voltage interval	x		Easy to calculate but do not contribute significantly to already achieved information by proposed indicators. However, it can be used as a complement to other indicators.
Minimum short circuit power	x		Data could be difficult to access or difficult to calculate if models are not available. Therefore, the indicator could be difficult to calculate.
Number of shunt manoeuvres	x	x	The indicators could be ambiguous, and data could be difficult to access and therefore the indicator could be difficult to calculate.
Amount of time with lack of available inductive and/or capacitive reserves		x	Data could be difficult to access and therefore the indicator could be difficult to calculate.

4.3.3 Visualisation of two selected voltage indicators

This section visualizes two of the selected voltage indicators for analyzing grid robustness. The voltage data used in this report are aggregated mean values for 3-phase RMS-voltage every 5 minutes. The measurements are done during the past year in one of the 400 kV stations owned by the Swedish transmission system operator Svenska kraftnät. The 400 kV station is located in the southern part of Sweden and there are static reactive devices (both capacitive and inductive) available in the station. However, by analyzing voltage data for this particular station there is probably a lack of voltage reserves in this area.

The data is not publicly available but was provided on demand by the Swedish TSO. Due to the lack of available data, it has not been possible to compute indicators 3 and 4.

Figure 14 presents indicator 1 *Number of minutes outside recommended voltage interval.* This indicator exhibits a large volatility, ranging from 4000 minutes outside of the interval in November 2023 to more than 10 000 minutes in August 2024. Indicator 3 *Amount of available inductive and capacitive reserves* would shed more light on whether this is due to less available voltage regulating reserves. Data was however unavailable. Indicator 4 *Number of nodes with more than X minutes outside recommended voltage interval* would capture whether the variations in the substation of Figure 14 are very local to this specific substation or visible even in more distant substations. Data was however unavailable to compute it.

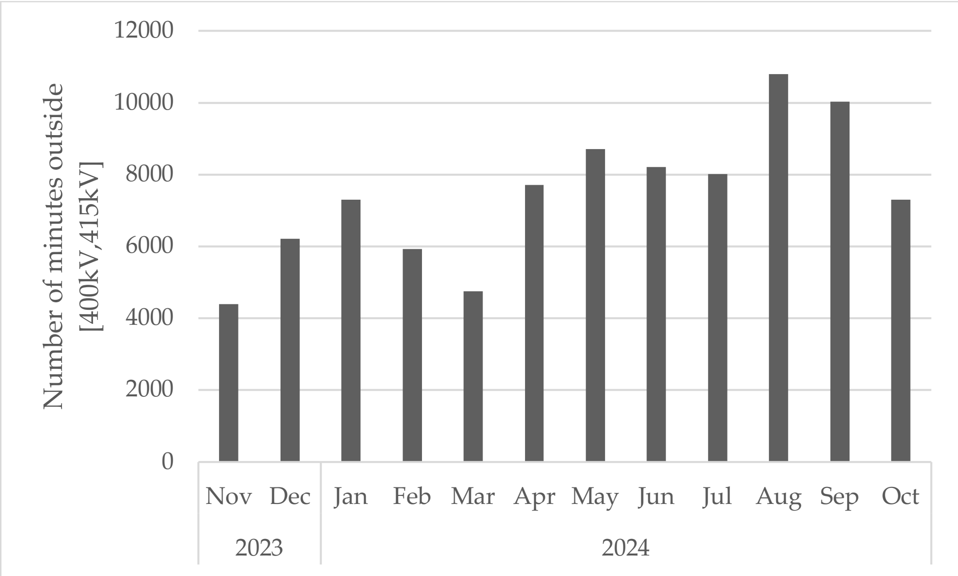

Figure 14: Number of minutes per month outside recommended voltage interval in one 400 kV substation of the Swedish national grid.

Figure 15 presents indicator 2 *Maximum/minimum voltage*. Variations are much smaller than the variations of indicator 1 in Figure 14, indicating no particular extreme events causing long voltage excursions (long enough to be captured by the 5-minute sampling rate of the available data).

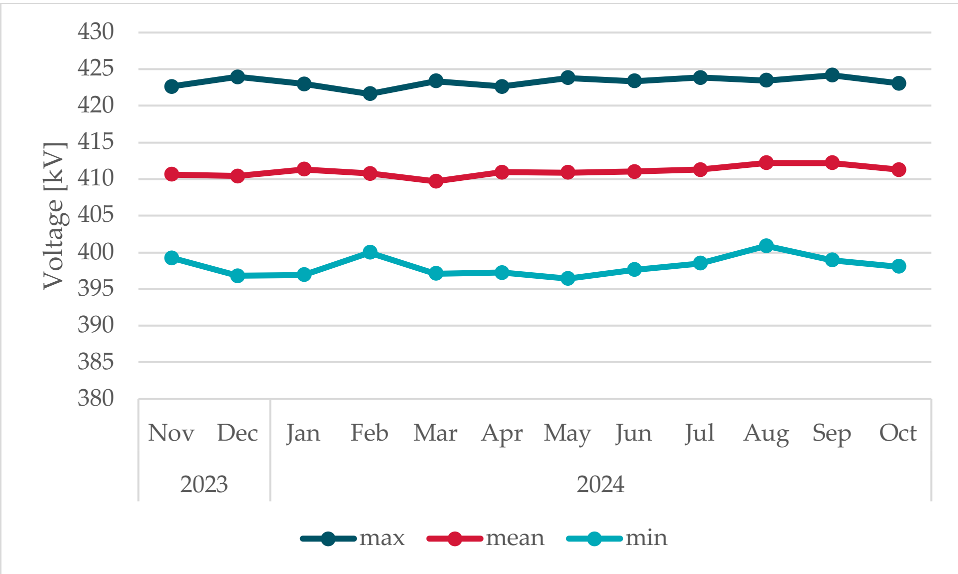

Figure 15: Monthly minimum and maximum voltage among all samples, and monthly mean voltage.

5 Conclusions

This project aimed at developing robustness, or quality, indicators for power systems. There is no agreed-upon definition of robustness in the field of power systems. Therefore, the work in this project has leaned upon the established framework of power system reliability, which has been used for several decades in the field. Power system reliability has traditionally been divided into resource adequacy, power system security, power quality. Recently, resilience has been added as another aspect of power system reliability.

It is not possible to capture the multifaceted nature of power system reliability with a single indicator, or even a handful of indicators. This project has instead developed a general framework and guiding principles that can be used to build indicators within each aspect of power system reliability. This framework and guiding principles make up a general set of rules that can be applied to any of the power system reliability aspects.

The framework is based on an event chain concept where any power system outcome, such as the system frequency, is the results of preconditions, unplanned events and measures taken by operators. The guiding principles state that, to measure for a specific aspect or outcome, indicators in each one of the four categories (preconditions, unplanned events, measures taken, and outcome) should be developed. In addition, indicators should be simple and unambiguous so that (1) they don't require a deep knowledge in the field of power system reliability to be understood and (2) changes in indicators can be unambiguously interpreted as beneficial or detrimental.

In this project, they have been applied to power system security and, more specifically, to frequency and voltage quality. The application of the set of rules to other aspects of power system security and, more generally, to other aspects of power system reliability is left as future work.

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ROBUSTNESS INDICATORS FOR POWER SYSTEMS

An event chain framework for developing power system robustness indicators is proposed, where a particular outcome of the power system, such as frequency or voltage at a substation, can be thought of as the result of preconditions, unplanned events and measures taken by system operators. Power system robustness with regards to this outcome can then be measured by developing a set of as few indicators as possible covering each one of these categories. This framework is applied to frequency and voltage quality. A set of indicators is proposed and computed for each one.

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