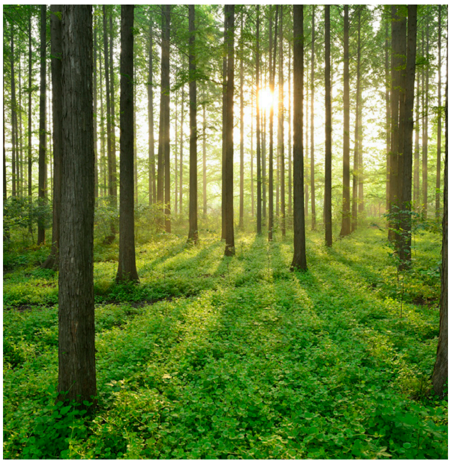
GRID-INDUCED MECHANICAL STRESS ON THE TURBINE-GENERATOR SHAFT

REPORT 2026:1216



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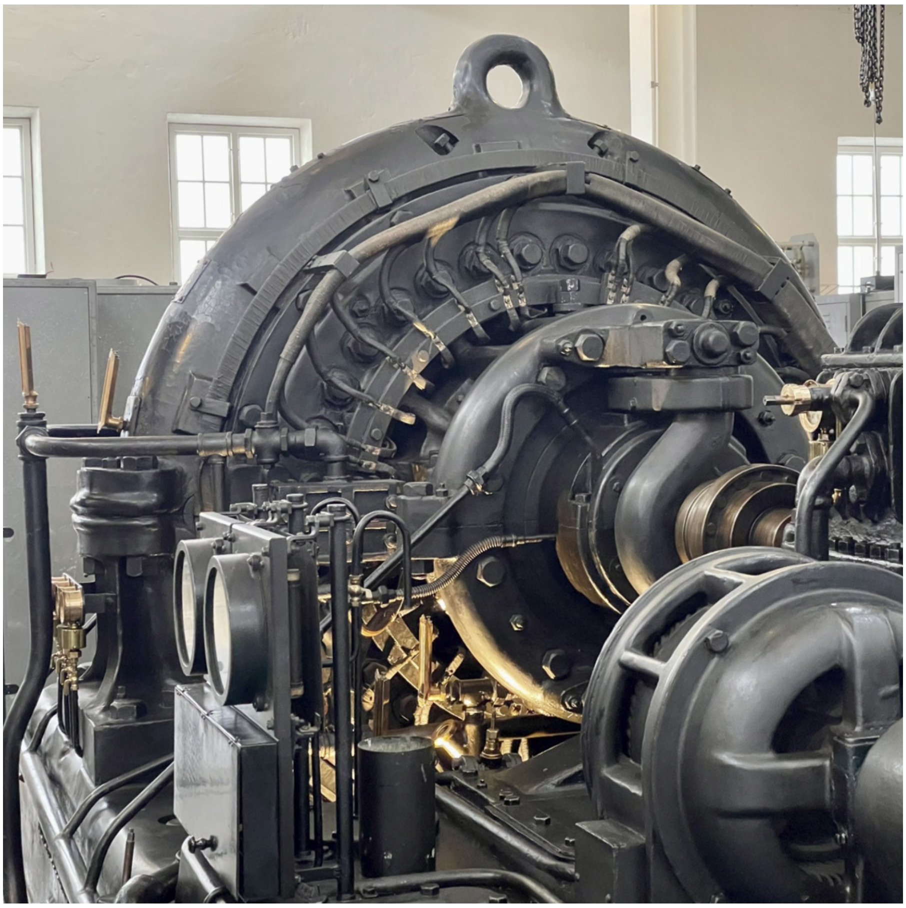

Energiforsk

Grid-induced mechanical stress on the turbine-generator shaft

Grid-induced mechanical stress, monitoring, and protection for Nordic NPPs

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Foreword

Grid disturbances increasingly challenge the mechanical integrity of nuclear power plant turbines, as the Nordic power system evolves with more renewables and power electronics. Investigating and assessing these risks is vital for plant safety and reliability.

This study aims to identify which grid events most affect turbine-generator mechanical integrity, evaluate risk factors and assess monitoring and protection solutions. It combines literature review, stakeholder interviews, and practical analysis.

Results show that improved monitoring, dedicated protection, and routine post-event analysis help make hidden risks visible and manageable. The report recommends practical steps to enhance safety, maintenance, and operational decision-making.

This report forms the results of a project performed within the Energiforsk Vibrations in Nuclear Applications Program, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi. The Vibrations program aims to increase the knowledge of causes, monitoring and mitigation of vibrations, thereby contributing to the safety, maintenance and development of a diverse range of machinery in the Nordic nuclear power plants.

The study was carried out by Henrik Hemark and Matilda Arvidsson, DNV.

Summary

From the perspective of an NPP turbine generator shaft, transients in the Nordic grid are increasingly experienced as short, sometimes repeated, torque disturbances. This project identifies which grid events matter most for mechanical integrity and shows why better measurements make a hard-to-detect risk visible and manageable in practice.

Grid disturbances reach the shaft as electromagnetic torque variations in the generator. Three event families are most relevant. First, faults, switching, and high-speed reclosing create transient torque impulses and residual torsional oscillations. Second, classic sub-synchronous resonance associated with series compensation can, in rare cases, sustain or amplify torsional motion if electrical and mechanical resonances align. Third, converter-driven interactions involving HVDC or inverter-based resources (IBR), including inverter-interfaced generation and inverter-interfaced loads (e.g., large industrial drives and future data centres), especially in weak-grid conditions, can reduce torsional damping and create oscillatory stress patterns that are difficult to recognise without dedicated monitoring.

The work combined a literature review, stakeholder interviews with Nordic NPPs, and an assessment of risk factors and existing solutions. A consistent conclusion is that the ability to observe torsional response varies between the plants. Where measurements are limited, damping and fatigue impact remain uncertain and decisions tend to rely on conservative margins. Where measurements and event recordings are stronger, plants can correlate electrical events with mechanical response and improve settings, maintenance planning, and coordination with the TSO and original equipment manufacturers (OEMs).

Practically, the report recommends maintaining dedicated torsional or SSR protection, upgrading vibration monitoring and event recording so that relevant electrical and mechanical waveforms are captured, and establishing routine post-event analysis. Improved measurement shortens investigations, supports evidence-based dialogue with the TSO and OEMs, and helps detect repeated non-tripping events before they accumulate into costly damage. The report also recommends revalidating studies and relay settings after major grid or plant changes.

Keywords

Keyword (English)	Sökord (Svenska)
Torsional vibration	Torsionsvibration
Sub-synchronous resonance (SSR)	Subsynkron resonans
Grid disturbance	Nätstörning
Nuclear power plant (NPP)	Kärnkraftverk
HVDC	HVDC (högspänd likström)
Fatigue accumulation	Utmattningsackumulering
Monitoring and protection	Övervakning och skydd
Phasor Measurement Unit (PMU)	Fasmätningsenhet
Mechanical integrity	Mekanisk integritet
Inverter-based resources	Omriktarbaserade resurser (IBR)

Sammanfattning

Ur ett kärnkraftverks turbin-generatoraxels perspektiv upplevs transienter i det nordiska kraftsystemet allt oftare som korta, ibland återkommande momentstörningar. Projektet identifierar vilka nätstörningar som är mest betydelsefulla för den mekaniska integriteten och visar varför bättre mätningar gör en svårupptäckt risk synlig och möjlig att hantera i praktiken.

Nätstörningar når axeln som elektromagnetiska momentvariationer i generatorn. Tre händelsefamiljer är mest relevanta. För det första ger fel, kopplingar och snabb återinkoppling transienta momentimpulser och kvarstående torsionssvängningar. För det andra kan klassisk subsynkron resonans kopplad till seriekondensatorer i nätet i sällsynta fall ge odämpade eller växande torsionsrörelser om elektriska och mekaniska resonanser sammanfaller. För det tredje kan omriktardrivna interaktioner med HVDC eller omriktarbaserade resurser (IBR), inklusive både omriktaransluten produktion och omriktaranslutna laster (t.ex. stora industriella drivsystem och framtida datahallar), särskilt vid svaga nätförhållanden, minska torsionsdämpningen och skapa oscillativa spännings- och lastmönster som är svåra att upptäcka utan specifik övervakning.

Arbetet kombinerade en litteraturstudie, intervjuer med nordiska kärnkraftverk och en bedömning av riskfaktorer och befintliga lösningar. En tydlig slutsats är att möjligheten att observera torsionsrespons skiljer sig mellan anläggningarna. Där mätningar är begränsade förblir dämpning och utmattningspåverkan osäkra och beslut baseras ofta på konservativa marginaler. Där mätningar och händelseregistrering är bättre kan anläggningen koppla elektriska händelser till mekanisk respons och förbättra inställningar, underhållsplanering och samverkan med TSO och originalutrustningstillverkare (OEM).

Rapporten rekommenderar att behålla dedikerade skydd för torsion eller SSR, att uppgradera vibrationsövervakning och händelseregistrering så att relevanta elektriska och mekaniska vågformer fångas, samt att införa rutinmässig efteranalys efter händelser. Förbättrade mätningar förkortar utredningar, stödjer en faktabaserad dialog med TSO och OEM och hjälper till att upptäcka återkommande händelser som inte ger frånkoppling innan de ackumuleras till kostsam skada. Rapporten rekommenderar även att studier och skyddsinställningar omprövas efter större förändringar i nätet eller i anläggningen.

Table of contents

List of figures

Abbreviations

Abbreviation	Meaning
ABB	Asea Brown Boveri (SSR protection vendor)
CIGRE	International Council on Large Electric Systems
DER	Distributed Energy Resource
DSO	Distribution System Operator
EMT	Electromagnetic Transient (simulation)
ENTSO-E	European Network of Transmission System Operators for Electricity
EPRI	Electric Power Research Institute
EXC	Exciter
FACTS	Flexible AC Transmission System
FFS	Fast Frequency Support
FRT	Fault Ride Through
GEN	Generator
HP	High-Pressure Turbine
HVDC	High Voltage Direct Current
IBR	Inverter-Based Resource(s)
IEEE	Institute of Electrical and Electronics Engineers
IGE	Induction Generator Effect
IP	Intermediate-Pressure Turbine
LCC	Line-Commutated Converter
LP1	Low-Pressure Turbine Stage 1
LP2	Low-Pressure Turbine Stage 2
MMC	Modular Multilevel Converter
NPP	Nuclear Power Plant
OEM	Original Equipment Manufacturer
PMU	Phasor Measurement Unit
PSC	Power System Consulting (Siemens PTI business area)
PSS	Power System Stabilizer
PSS/E	Power System Simulator for Engineering (Siemens software)
PTI	Power Technologies International
RoCoF	Rate of Change of Frequency
SCC	Short-Circuit Capacity

SSR	Sub-Synchronous Resonance
SSO	Sub-Synchronous Oscillation
SSTI	Sub-Synchronous Torsional Interaction
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
TI	Torsional Interaction
TCSC	Thyristor-Controlled Series Compensation
TSO	Transmission System Operator
UIF	Unit Interaction Factor
VSC	Voltage Source Converter

1 Introduction

1.1 BACKGROUND AND MOTIVATION FOR THE STUDY.

Electrical faults that may cause mechanical damage to turbines and generators have been a subject of study in the electric power engineering industry for at least 50 years. Notably, the sub-synchronous resonance event at Mohave power station in the early 1970s, which resulted in shaft cracks, sparked significant interest in this area (Anderson et al., 1999; EPRI, 2006). Since then, several studies, both in Sweden and internationally, have investigated grid events that can lead to mechanical damage in power plant components (EPRI, 2006; IEEE, 1985).

The Nordic power system is currently undergoing rapid and significant changes, driven by the expansion of renewable generation connected via power electronics, HVDC, and other advanced technologies, as well as the growth of inverter-based resources (IBR) more broadly (Energiforsk, 2021:835; Energiforsk, 2025:1091). These developments have increased the need to study various types of disturbances and their potential consequences for both nuclear power plants and the transmission grid. Mechanical damage to turbines and main generators in nuclear power plants can result in substantial costs due to component replacements, repairs, and extended outages. Beyond plant-level repair costs, a forced outage of a large synchronous unit can also reduce system services such as inertia and voltage support, constrain power-transfer capability, and increase the operational burden on the TSO, especially during stressed or weak-grid conditions. Ensuring awareness of relevant disturbances and effective monitoring and protection strategies is therefore essential for maintaining safe and stable operation.

1.2 PROJECT OBJECTIVES

The primary aim of this project is to define, in a Nordic context, the grid events that may result in mechanical damage to turbines and main generators in nuclear power plants. This will be achieved through a comprehensive literature review and by collecting information from Nordic nuclear power plants (with additional input from the reference group, including TSO-originating material where available). Once the relevant grid events are identified, the project will analyse factors that may impact the risk for nuclear power plants and evaluate existing solutions for monitoring and protection.

A key aim of this project is to identify and monitor not only major grid disturbances that lead to trips, but also moderate, repeated events that may not trigger immediate protection but can accumulate mechanical fatigue and pose a risk of sudden failure (Energiforsk, 2016:295; EPRI, 2006). These ‘non-obvious’ risks are particularly important to detect early, as they may otherwise go unnoticed until a critical incident occurs. The project therefore places special emphasis on developing monitoring strategies and analysis routines that can capture and assess the impact of such disturbances, supporting proactive risk management for nuclear power plants and their stakeholders.

1.3 RELEVANCE FOR STAKEHOLDERS

This project is highly relevant given the ongoing transformation of the Nordic transmission grid and the increasing integration of new technologies. The outcomes are expected to provide valuable input for stakeholders to maintain the secure and reliable operation of Nordic nuclear power plants in the evolving power system. The project is carried out in close collaboration with Energiforsk's Vibrations programme, Nordic nuclear power plants, and a reference group. The Vibrations programme has defined the project scope and direction and will review whether the project results meet the intended objectives. The reference group also includes representatives from the GINO programme, contributing expertise on electrical grid and power-electronics aspects. Where available, TSO-originating data have also been presented to support the discussion.

1.4 PROJECT PARTNERS AND STRUCTURE

The assignment has been executed by DNV Sweden AB, with a project team comprising senior engineers and specialists in power system analysis. The work has been conducted in three main steps:

1. Literature review of relevant grid events,
2. Interviews with stakeholders,
3. Analysis of risk factors and existing solutions.

The results have been compiled and reported together with practical recommendations and disseminated through meetings and presentations to the reference group and stakeholders.

1.5 CONTENT AND ORGANISATION OF THIS REPORT

The report is structured to move from technical background to practical stakeholder experience and finally to recommendations. Chapter 0 summarises the mechanisms by which grid events can excite turbine–generator shafts and reviews relevant historical experience and recent developments in the Nordic power system. Chapter 3 presents the stakeholder interview methodology and synthesises the input from Nordic NPPs, highlighting common themes and differences in practices and observability.

Building on these inputs, Chapter 4 analyses which combinations of grid conditions (e.g. weak-grid operation, topology changes, series compensation exposure, converter-dominated interactions) and unit characteristics (e.g. torsional eigenfrequencies, uncertain damping) plausibly drive mechanical risk, and evaluates how current monitoring and protection solutions perform under those conditions. Chapter 5 consolidates the findings into conclusions and recommendations at both the system level (e.g. predictable study processes and data exchange between TSOs and plants) and the plant level (e.g. clear event-response routines, measurement strategies), with the aim of supporting operational decisions with an appropriate, transparent evidence base. References are provided in the bibliography, and the interview questionnaire is included in the appendix.

2 Technical Background

2.1 FUNDAMENTALS OF TORSIONAL INTERACTION BETWEEN ELECTRICAL NETWORKS AND TURBINE-GENERATOR SHAFTS

Electrical disturbances in the power system can generate electromagnetic torque variations in synchronous generators (EPRI, 2006; IEEE, 1985). These torque variations act on the turbine–generator shaft and may excite its natural torsional modes, depending on the disturbance spectrum, duration, and available damping (EPRI, 2006; Siemens PTI, 2018). Depending on disturbance spectrum, duration, and damping, the mechanical effect may range from negligible oscillations to accelerated fatigue accumulation and, in rare cases, mechanical damage, as demonstrated in historical incidents and subsequent studies (IEEE, 1985; Energiforsk, 2016:295).

2.2 CONCEPTUAL COUPLING BETWEEN GRID DISTURBANCES AND THE MULTI-MASS TURBINE–GENERATOR SHAFT

Building on the conceptual coupling described above, electrical disturbances in the power system can give rise to dynamic electromagnetic torque variations in synchronous generators. These torque variations act directly on the generator rotor and are transmitted along the turbine–generator shaft, which is typically composed of multiple masses connected by elastic shaft segments. The fundamental coupling between electrical network dynamics and mechanical shaft dynamics has been well documented in industry and research literature over several decades, particularly in the context of sub-synchronous resonance and related torsional interaction phenomena (EPRI, 2006; IEEE, 1985).

From a physical perspective, the coupling mechanism can be described as a causal chain: electrical disturbances in the grid introduce sub-synchronous or transient current components in the stator, which in turn produce oscillatory electromagnetic torque in the air-gap of the generator (EPRI, 2006; IEEE, 1985). This oscillatory torque excites the natural torsional modes of the multi-mass turbine–generator shaft, leading to angular speed oscillations and cyclic mechanical stresses in specific shaft sections. Depending on the proximity of the excitation frequencies to the shaft's natural modes and the available damping, the resulting response may be properly damped, weakly damped, sustained, or, in rare cases, growing (EPRI, 2006; Siemens PTI, 2018).

Repeated excitation of torsional modes, even at relatively low amplitudes, may contribute to cumulative fatigue damage over time, particularly in mechanically sensitive locations such as couplings or shaft transitions (Energiforsk, 2016:295; IEEE, 1985). More severe events may result in protection operation or, in exceptional cases, mechanical damage. Historical incidents and subsequent studies have demonstrated that such damage mechanisms are driven by the interaction between electrical and mechanical systems rather than by purely mechanical loading alone (IEEE, 1985; Energiforsk, 2016:295).

Figure 2-1 provides a conceptual illustration of this coupling. Grid disturbances such as short-circuit faults, switching events, or control-driven interactions associated with HVDC links or other power-electronic devices are shown as the initiating cause, consistent with established industry guidance and previous studies of torsional interaction phenomena (EPRI, 2006; Siemens PTI, 2018). These disturbances give rise to electromagnetic torque variations in the generator, which excite the torsional dynamics of the multi-mass turbine–generator shaft system. The mechanical consequences include torsional vibration, local stress concentration, fatigue accumulation, and potential protection operation. The figure is intended as a high-level explanatory illustration rather than a detailed analytical or unit-specific model, in line with common practice in industry guidance and technical reports (EPRI, 2006; Siemens PTI, 2018).

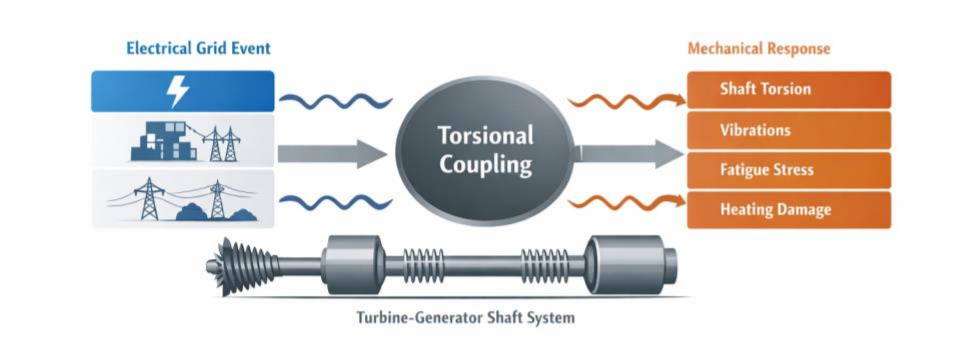

Figure 2-1. Conceptual illustration of the coupling between electrical grid events and mechanical response in a turbine–generator shaft system. Electrical disturbances give rise to electromagnetic torque variations, which can excite torsional modes in the multi mass shaft system and lead to vibrations and fatigue related mechanical effects. [AI-generated schematic]

This conceptual view forms the basis for the subsequent classification of grid events and interaction mechanisms discussed in the following sections, including general torsional interaction during faults and switching, classical sub-synchronous resonance associated with series compensation, and device-dependent sub-synchronous oscillations driven by HVDC or other power-electronic systems.

Before classifying disturbance types, it is useful to review how sub-synchronous phenomena have been encountered and managed in practice. The next section summarises historical experience in Europe and the Nordic region – from early SSR incidents such as Mohave to the preventive measures that shaped today's practices.

2.3 HISTORICAL EXPERIENCE WITH SUB-SYNCHRONOUS PHENOMENA IN EUROPE AND THE NORDIC POWER SYSTEM

The sub-synchronous resonance (SSR) incidents at the Mohave power station in the early 1970s are still used as a reference case in European and Nordic literature, as they represent a rare situation where a series-capacitor-induced electrical resonance coincided with a lightly damped torsional eigenmode of a turbine–generator shaft, resulting in documented shaft cracking and mechanical failure. These events established SSR as an electromechanical phenomenon and directly influenced subsequent protection philosophies, study practices, and grid-connection requirements (IEEE, 1985; EPRI, 2006).

In European and Nordic power systems, no publicly documented cases of turbine–generator shaft cracking attributable to sub-synchronous phenomena have been reported. This absence of mechanical failure does not imply absence of risk. Instead, it reflects early recognition of the phenomenon and systematic implementation of preventive measures by transmission system operators (TSOs), plant owners, and OEMs following the Mohave experience. European technical literature and protection guidance explicitly describe Mohave as the historical driver for conservative design margins, mandatory screening studies, and early deployment of torsional protection (Siemens PTI, 2018; ENTSO-E, 2017).

2.3.1 Nordic experience: identified risk and preventive mitigation

In the Nordic transmission system, series compensation was introduced relatively early on long 400 kV corridors. Several publications state that the first 400 kV series-compensation project was energised in Sweden in 1954. From the outset, SSR was recognised by Svenska kraftnät and plant owners as a credible risk for large thermal and nuclear units, while hydro units were generally assessed as less sensitive due to shorter and stiffer shaft systems. Consequently, conservative compensation levels, systematic SSR studies, and operational constraints were applied in proximity to sensitive generation.

A well-known Swedish example is the Stöde series-compensation installation, where thyristor-controlled series compensation (TCSC) was deliberately selected to avoid fixed electrical resonances and thereby reduce SSR risk. Contemporary Nordic and European publications describe this installation as an example of preventive application of controllable FACTS technology, explicitly motivated by lessons learned from Mohave rather than by response to observed mechanical damage (Modern Power Systems, 1995; Siemens PTI, 2018).

A particularly important Nordic case is a long-term field study performed at a Swedish nuclear power plant, where measurements at generator terminals captured both sub-synchronous and super-synchronous current components, together with signatures consistent with torsional interaction. The work did not result in shaft damage but demonstrated sufficiently low damping and repeated excitation to justify the installation of dedicated numerical SSR protection. The case is frequently cited in protection literature as one of the closest Nordic analogues to the Mohave events, with the key distinction that detection and mitigation occurred before mechanical failure (Kockott et al., 2020; IEEE, 1985).

2.3.2 Continental European experience: SSTI and non-classical mechanisms

In continental Europe, sub-synchronous phenomena have also been observed, often with characteristics differing from classical series-capacitor-driven SSR. In particular, the extensive use of HVDC interconnections has introduced the risk of sub-synchronous torsional interaction (SSTI), where converter control dynamics interact with nearby synchronous generators and their mechanical shaft systems without the presence of series-compensated AC lines (Bornard et al., 1988).

Such interactions have been recognised in European TSO and OEM literature since the 1980s and are explicitly addressed in ENTSO-E guidance and network-code implementation documents, consistent with international study guidelines (CIGRE, 2014). These documents require assessment of sub-synchronous torsional interactions between HVDC systems and nearby generation as part of grid-connection and system-integration studies, reflecting that these phenomena have been observed in practice even though no publicly reported shaft failures have occurred (ENTSO-E, 2017).

Recent IEEE PES task-force work also surveys multiple real-world sub-synchronous oscillation events associated with high penetrations of inverter-based resources, highlighting that such phenomena can be influenced by grid characteristics such as series compensation and low system strength and motivating updated study and mitigation workflows.

European OEM and utility publications further describe near-miss situations for large thermal units connected close to series-compensated corridors, particularly under radial or weak-grid conditions. In several documented cases, sustained sub-synchronous currents or poorly damped oscillations were identified through studies or measurements, leading to operational restrictions, derating, or tripping before mechanical damage occurred. This pattern, verified observation followed by preventive action, is consistently described in European protection and SSR literature (Siemens PTI, 2018; IEEE, 1985).

2.3.3 Engineering perspective

From an engineering and regulatory perspective, the Nordic and European experience demonstrates that sub-synchronous phenomena—including SSR, SSTI, and broader sub-synchronous oscillations—are real and observable in the field. However, systematic screening, conservative application of series compensation, use of controllable FACTS devices, and early deployment of dedicated torsional protection have, to date, been effective in preventing Mohave-type mechanical failures. These practices form the basis of current Nordic TSO requirements, European grid-code provisions, and industry best practice.

These historical lessons confirm the reality of sub-synchronous risks and the value of preventive action. Building on that understanding, the next section categorises the grid disturbances most relevant to turbine–generator shafts, grouping events into three broad families to structure the subsequent analysis.

2.4 OVERVIEW OF GRID EVENTS WITH MECHANICAL RELEVANCE

To structure the discussion from a turbine–generator shaft perspective, the grid disturbances most relevant for mechanical integrity are grouped into three broad families that cover most practical cases in Nordic networks:

i. General torsional interaction from faults, switching, and high-speed reclosing (transient torque amplification and residual oscillations).

ii. Classic Sub-Synchronous Resonance (SSR) associated with series-compensated corridors (sustained/growing sub-synchronous oscillations, torque amplification).

iii. Device-dependent sub-synchronous oscillations (SSTI/SSO) driven by control interactions of HVDC, SVC/STATCOM, or inverter-based resources (IBR).

In addition to these families, recent European disturbance investigations underline that voltage-driven cascading disconnection sequences (multiple trips and topology changes within minutes) can be a practical amplifier of mechanical duty by creating repeated switching and non-stationary operating conditions. Such sequences are discussed in the ENTSO-E investigation of the Iberian blackout (Section 2.5.3) and in other significant event investigations that highlight the importance of disturbance reconstruction and coordinated protection practice (ENTSO-E, 2022; ENTSO-E, 2026). They are therefore kept in scope here as a 'system escalation' pathway rather than as a distinct torsional mechanism.

In this report, sub-synchronous oscillations (SSO) are used as the umbrella term for sub-synchronous phenomena; SSR refers to the classical series-compensation resonance case, while SSTI denotes torsional interactions driven by control dynamics (e.g., HVDC or other power-electronic devices).

2.4.1 General torsional interaction

Sudden changes in electrical conditions – such as short-circuit faults, fault clearing, or high-speed reclosing – produce transient electromagnetic torque disturbances in synchronous generators. As described in Section 2.1, these torque impulses propagate through the turbine–generator shaft and can excite one or more natural torsional modes of the multi-mass system.

Simulations and analytical studies of large steam turbine–generator units show that (EPRI, 2006; Energiforsk, 2016:295):

- close-in faults (including generator-terminal and nearby bus faults) can produce high torque impulses, depending on fault type, clearing time, and system conditions,
- different fault types (single-phase, two-phase, three-phase) lead to different torque and speed responses,
    - depending on the unit and network conditions, some studies report higher torque peaks for certain unbalanced fault types; the most critical fault type can differ by unit and by shaft location
- residual oscillations may persist after fault clearing, contributing to cumulative fatigue even when no immediate damage occurs,
- high-speed reclosing may re-excite torsional modes and should be represented in duty-cycle assessments.

Although such events typically do not produce sustained oscillations, and even when frequencies do not coincide with exact natural modes, post-fault residual oscillations contribute to fatigue over many events and make them relevant for mechanical integrity assessments. In systems with changing inertia levels and altered protection philosophies, the dynamic severity of otherwise familiar events may increase.

Figure 2-2 schematically illustrates the excitation of torsional modes following a generic grid fault and subsequent reclosing. The turbine–generator shaft system can be represented by a lumped mass–spring model. In this representation, each major rotor section is modelled as an individual inertia: the high-pressure turbine (HP), low-pressure turbine stages (LP1–LP3, where applicable), the generator rotor (GEN), and the exciter (EXC). Nordic units differ somewhat in how the low-pressure turbine is partitioned into casings/rotor modules (vendor- and design-dependent), and therefore in whether the shaft-line model is labelled LP1–LP2 or LP1–LP3; in this report, LP1–LP3 is used as a generic label for the low-pressure turbine section, with the exact number of LP stages being unit-specific. These inertias are connected by torsional springs that represent the stiffness of the shaft segments between the respective turbine and generator sections. For illustration, Figure 2-2 uses indicative relative inertia shares. Based on reference-group input and comparison with unit-specific shaft-line data from Swedish nuclear units, the indicative relative inertia ranges used for this conceptual illustration are shown below. The values are deliberately presented as approximate ranges rather than exact unit data, since detailed shaft-line inertia data are unit-specific and not publicly disclosed.:

- HP 2 – 5%
- LP1–LP3 80 – 88% (total)
- GEN/EXC 10 – 15%

The purpose of the figure is conceptual (to show how electromagnetic torque disturbances originating at the generator end propagate along the shaft line and how relative inertias influence torsional response), rather than to define a single set of universal percentages.

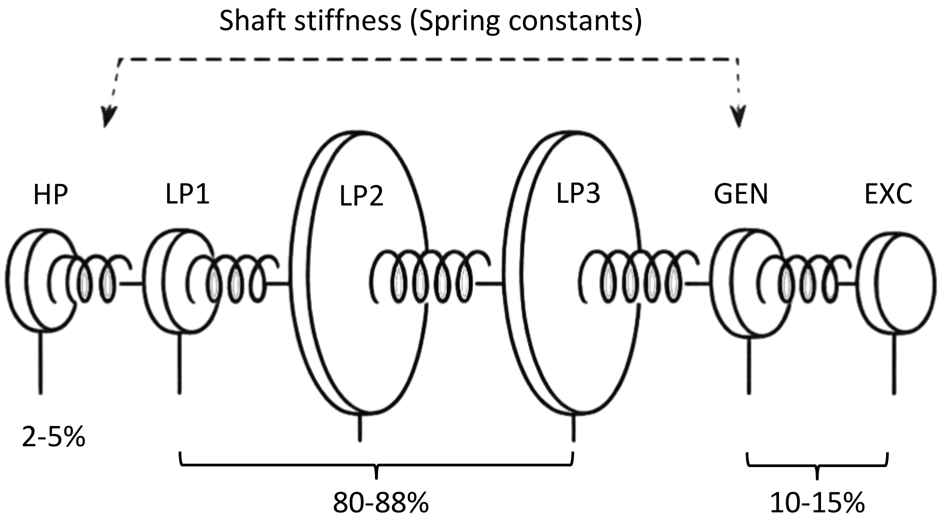

Figure 2-2. Simplified (not to scale) lumped mass–spring model of the turbine–generator shaft showing rotor inertias and torsional stiffness segments between turbine and generator stages. Percentages indicate typical relative inertia contributions of the main rotor sections. [AI-generated schematic]

2.4.2 Sub-synchronous resonance

Sub-synchronous resonance (SSR) is a specific type of electromechanical interaction – essentially the coupling mechanism from Section 2.1 applied to a resonant network scenario. It occurs when an electrical network resonance (classically due to series-compensated transmission lines) coincides with a turbine–generator's sub-synchronous torsional natural frequency. Under such conditions, sustained or growing oscillations can develop. Depending on system conditions, SSR may manifest as:

- induction generator effect (IGE),
- torsional interaction (TI), or
- transient torque amplification.

As noted in Section 0, the historical Mohave incidents (early 1970s) demonstrated that SSR could indeed lead to shaft cracking and severe mechanical damage. This rare but pivotal case sparked decades of research and led to standard analysis methods (frequency scans, small-signal stability studies, detailed EMT simulations). In Nordic and European practice, Mohave's legacy was primarily preventative: conservative series-compensation limits, mandatory SSR screening studies, and early deployment of torsional protection were all implemented long before any local mechanical failures occurred.

While explicit series compensation near Nordic NPPs may be limited, SSR risk can still arise via topology changes, contingency flows, or distant compensated corridors; systematic frequency scans + EMT time-domain validation remain the standard workflow. SSR remains relevant due to:

- long-distance transmission corridors,

- evolving network topologies, and
- changes in power flow patterns associated with the Nordic power system transformation.

Figure 2-3 provides a conceptual illustration of classical SSR arising from a series-compensated transmission line interacting with turbine–generator torsional modes. A grid fault and subsequent reclosing produce electromagnetic torque disturbances at the generator, exciting torsional modes in the shaft. The mechanical response may include transient vibrations, fatigue accumulation, or protection operation, depending on system damping.

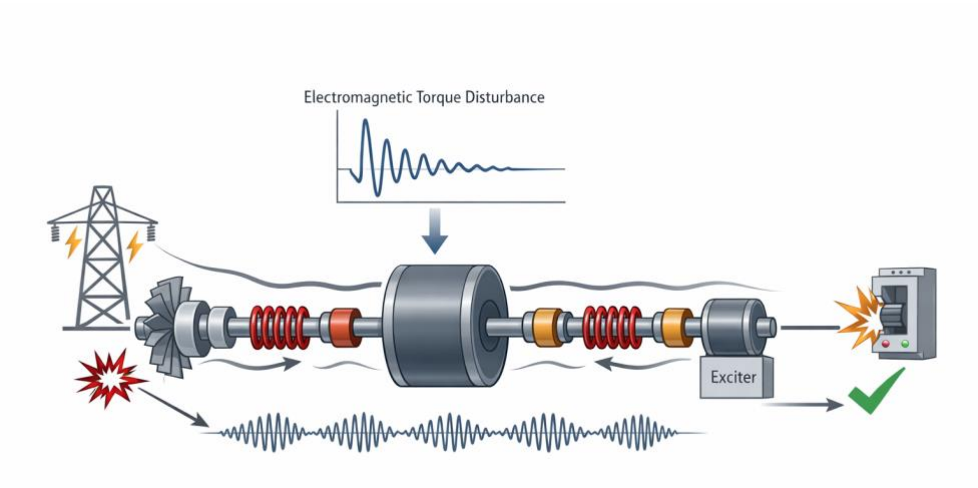

Figure 2-3. Conceptual schematic illustrating how a grid fault and subsequent reclosing can produce transient electromagnetic torque disturbances at the generator and excite torsional modes in the turbine–generator shaft system. The resulting mechanical response may range from transient torsional vibration to cumulative fatigue damage and, in some cases, protection operation, depending on the system's damping and operating conditions. [AI-generated schematic]

2.4.3 Device-dependent sub-synchronous oscillations

In modern power systems, sub-synchronous torsional interactions are no longer limited to series-compensated AC lines. Power-electronic devices with fast control systems, such as HVDC converters, static VAR compensators (SVC/STATCOM), and inverter-based resources (IBR) can interact with turbine–generator shafts through their control dynamics. In this report, IBR is used as a broad term that includes inverter-interfaced generation as well as inverter-interfaced loads (e.g., large industrial drives and data centres) and other converter-connected devices.

Such interactions fall under the umbrella term sub-synchronous oscillations (SSO) and are often discussed specifically as sub-synchronous torsional interaction (SSTI). Unlike classical SSR, these phenomena may:

- occur without series compensation,
- depend strongly on converter control settings and operating points, and
- be sensitive to system strength and topology.

Documented incidents since the late 1970s have shown that HVDC systems can reduce the effective damping of torsional modes or even introduce negative damping under certain conditions (Du et al., 2019; ENTSO-E, 2017). Guidance has long recognised that inverter-based resources can contribute to oscillatory phenomena in the sub-synchronous frequency range, particularly in weaker grids and under certain network configurations (CIGRE, 2014). More recent surveys and updated guidance further document such events and motivate updated study and mitigation workflows (IEEE PES IBR SSO Task Force, 2022; CIGRE, 2023).

Beyond sub-synchronous ranges, converter-dominated systems can also exhibit forced oscillations and weakly damped modes at lower frequencies. The ENTSO-E Iberian blackout investigation (Section 2.5.3) highlights the operational importance of oscillation detection and time-synchronised recordings (PMUs and oscillography) to reconstruct such events and to distinguish control-driven interactions from classical network resonances.

Given the increasing penetration of HVDC links and inverter-based resources (IBR) in the Nordic power system, device-dependent sub-synchronous oscillations are considered a key emerging risk category for large turbine–generator units.

Typical interaction paths between HVDC or inverter-based resources and a nearby turbine–generator include the following:

- LCC and MMC/VSC HVDC control loops can reduce torsional damping or create negative damping at sub-synchronous frequencies, even without series compensation.
- Large inverter-based resource (IBR) clusters (e.g., wind/PV/STATCOM) in weak grids can introduce control-driven SSO (often 10–30 Hz) that propagate to nearby synchronous units.
- Severity depends on short-circuit strength, operating point, set-points, and controller bandwidths, requiring scenario-based analysis.

2.5 HISTORICAL CONTEXT AND PREVIOUS STUDIES

This section summarizes key studies and mitigation strategies for torsional vibrations and sub-synchronous resonance (SSR) in large synchronous generators, particularly those used in nuclear power plants. The content is based on EPRI, Energiforsk, IEEE, and industry references (EPRI, 2006; Energiforsk, 2016:295; IEEE, 1985; Siemens PTI, 2018).

- Decades of research document SSR incidents (e.g., Mohave) and HVDC-related SSTI, alongside IBR-driven SSO mechanisms documented in later surveys and updated guidance (Anderson et al., 1999; EPRI, 2006; CIGRE, 2014; IEEE PES IBR SSO Task Force, 2022; CIGRE, 2023).
- Methodologically, industry practice combines screening (frequency scans, modal torque coefficients) with detailed EMT studies and measurement-based validation (PMU and relay records) (EPRI, 2006; CIGRE, 2014; ENTSO-E, 2026).

2.5.1 Key Technical Reports and Studies

EPRI Reports:

While the EPRI reports cited below are foundational references and remain widely used, more recent public guidance on converter-dominated and IBR-related SSO is available in CIGRE Technical Brochure 909 and recent IEEE task-force work (CIGRE, 2023; IEEE PES IBR SSO Task Force, 2022).

- Torsional Interaction Between Electrical Network Phenomena and Turbine-Generator Shafts – foundational reference for SSR and torsional interaction (EPRI, 2006).
    - Purpose: Provide an overview of electromechanical coupling mechanisms between electrical-network phenomena and multi-mass turbine–generator shaft systems, and outline practical study and assessment approaches.
    - Key findings: Identifies the main excitation categories (fault/switching transients, series-compensation-related SSR, and control-driven interactions) and highlights that damping and unit-specific shaft data are critical but often uncertain, motivating conservative screening and protection philosophies.
    - Relevance: Serves as a primary industry reference for framing risk mechanisms, selecting appropriate study methods (screening vs detailed simulation), and motivating monitoring/protection requirements for large units exposed to grid transients and sub-synchronous phenomena.
- Steam Turbine-Generator Torsional Vibration Interaction with the Electrical Network – details SSR effects and historical failures (EPRI, 2005).
    - Purpose: Provide a tutorial-style treatment of how electrical-network disturbances and resonances interact with steam turbine–generator shaft torsional modes, including typical modelling representations and response characteristics.
    - Key findings: Summarises the characteristic response of turbine–generator shafts to network transients and resonant conditions, illustrates why certain configurations and operating conditions can lead to elevated cyclic stress, and describes the role of protection and operational constraints in preventing damage.
    - Relevance: Provides practical background for interpreting torsional response mechanisms and for communicating SSR-related concepts to stakeholders; supports the report’s emphasis on combining studies, protection, and measurements to manage both rare high-consequence events and repeated moderate disturbances.

Energiforsk reports:

- Fast Frequency Support Impact on Nuclear Generation (Energiforsk, 2025:1145)
  - Purpose: Investigate how Fast Frequency Support (FFS) from HVDC links interacts with synchronous generators in nuclear power plants.
  - Key Findings: FFS can induce rapid dynamic effects on generator control systems and affect stability during grid disturbances.
  - Relevance: Vibration phenomena may arise during rapid frequency changes—this report provides insight into mechanisms that can trigger such events.
- Impact of Over-Frequency Events on Nordic NPPs (Energiforsk, 2025:1118)
  - Purpose: Quantify over-frequency events in the Nordic system and analyse their impact on nuclear power plants.
  - Key Findings: Simulations show that HVDC faults and low system inertia increase the risk of over-frequency, which can stress turbines and generators.
  - Relevance: Over-frequency can cause mechanical vibrations in the turbine-generator chain—directly linked to the objectives of this study.
- Trends of Frequency Deviations (Energiforsk, 2025:1091)
  - Purpose: Map frequency deviations and inertia trends in the Nordic region over two decades.
  - Key Findings: Reduced inertia and increased wind power correlate with more frequent and larger frequency deviations; interviews with NPP owners confirm increased wear.
  - Relevance: Provides background data for understanding long-term risks of vibration problems related to frequency variations.
- Voltage Dip Transients and Auxiliary Equipment in Nuclear Power Stations (Energiforsk, 2025:1090)
  - Purpose: Analyse the origin and propagation of voltage dips and their impact on auxiliary systems.
  - Key Findings: Transients can disrupt auxiliary systems and increase the risk of mechanical stress.
  - Relevance: Voltage dips can induce vibrations in equipment and affect system robustness—important for a comprehensive analysis.
- Characterization of "Big Events" (Energiforsk, 2022:883)
  - Purpose: Describe and analyse major grid disturbances and their consequences for nuclear power plants.

- Key Findings: Identifies critical events where remaining nuclear units played a key role in system stability.
- Relevance: Provides scenarios for extreme grid impacts that can lead to vibration problems in machinery.

- Impact on Nuclear Power Plant Operation of a Changing Generation Mix (Energiforsk, 2021:835)
  - Purpose: Study how the transition to more power electronics and less synchronous mass affects NPP operation.
  - Key Findings: Changed system dynamics increase the risk of instability and interactions with NPPs.
  - Relevance: Vibration risks increase as grid properties change—this report provides context for future scenarios.
- Sub-Synchronous Oscillations (Energiforsk, 2020:707)
  - Purpose: Evaluate risks of sub-synchronous oscillations between synchronous generators and VSC units.
  - Key Findings: Identifies methods for analysis and risk assessment of oscillations that can cause mechanical damage.
  - Relevance: Directly related to torsional and vibration phenomena in converter-rich systems and therefore a key reference for this study.
- Torsional and Stator Vibrations in Turbines and Generators (Energiforsk, 2016:295)
  - Purpose: Analyse torsional and stator vibration phenomena in Nordic nuclear power plants and propose mitigation actions.
  - Key Findings: Identifies vibration risks in turbines and generators and evaluates mitigation strategies implemented at several plants.
  - Relevance: Directly addresses vibration mechanisms and practical solutions—essential background for this study.
- Sub-Synchronous Oscillations – Grid Interference on Nuclear Power Plant Operations (Energiforsk, 2017:355)
  - Purpose: Assess risks of sub-synchronous resonance (SSR) and grid-induced oscillations in nuclear power plants.
  - Key Findings: Details SSR risks, analysis methods, and protection strategies for nuclear units exposed to grid disturbances.
  - Relevance: Provides foundational knowledge on SSR and grid interaction risks—highly relevant for vibration studies.

- Development of a Digital Twin for Torsional Vibrations of Turbogenerators (Energiforsk, 2025:1084) – advanced monitoring and modelling.
  - Purpose: Develop advanced monitoring and modelling tools (digital twin) for torsional vibrations in turbogenerators.
  - Key Findings: Presents a digital twin approach for real-time monitoring and predictive analysis of torsional vibration risks.
  - Relevance: Offers state-of-the-art methods for vibration analysis and monitoring—valuable input for the approach in this study.

IEEE publications:

- IEEE Guide for AC Generator Protection (IEEE Std C37.102) – comprehensive guide on protection schemes for large synchronous generators (IEEE, 2006).
  - Purpose: Provide application guidance for protection of large synchronous generators and their excitation systems, covering faults and abnormal operating conditions.
  - Key findings: Summarises commonly applied protection functions and coordination considerations for generator units, supporting consistent selection and settings of protective relays in utility practice.
  - Relevance: Complements torsional/SSR-specific guidance by defining the baseline generator-protection context in which SSR relays, event recorders, and post-event procedures operate.
- Turbine-generator shaft torsional vibrations resulting from transmission line transients – working group paper consolidating industry experience on torsional effects from network events (IEEE, 2012).
  - Purpose: Consolidate and document industry understanding of turbine–generator shaft torsional vibrations initiated by transmission-network transients, including typical mechanisms, observations, and study considerations.
  - Key findings: Highlights that certain transmission-line disturbances can excite torsional modes, and that observability and interpretation may be challenging without suitable recording and analysis; stresses the importance of study assumptions and unit-specific data.
  - Relevance: Supports the report’s focus on fault/switching/reclosing events as a practical excitation family and motivates measurement/recording capabilities to link electrical disturbances to shaft response.

CIGRE and conference publications:

- Challenges and Solutions for Numerical Sub-Synchronous Resonance Protection – practical implementation and field evidence from a Nordic nuclear context (Gajić et al., 2024).
    - Purpose: Present measurement-based development and implementation considerations for numerical SSR protection, using long-term field recordings of sub- and super-synchronous components as an input to protection design.
    - Key findings: Demonstrates that sustained or recurring sub-synchronous components can be captured at generator terminals and substations, and that practical numerical implementations can be built using standard relay functions combined with filtering/measurement logic.
    - Relevance: Provides a Nordic, practice-oriented example of how measurement data can inform protection philosophy and settings—directly aligned with the report's emphasis on observability and learning from non-obvious events.
- Guidelines for Subsynchronous Oscillation Studies in Power Electronics Dominated Power Systems (CIGRE Technical Brochure 909) – guidance on SSO classification, study methods, and mitigation/monitoring in converter-rich systems (CIGRE, 2023).
    - Purpose: Provide guidelines for identifying, screening, and analysing sub-synchronous oscillations in modern power systems with significant power-electronic interfaces.
    - Key findings: Proposes an updated classification of SSO (including power-electronic device interactions), and presents a systematic study process from screening (e.g., frequency/impedance scans) to detailed EMT studies, together with mitigation and monitoring/protection considerations.
    - Relevance: Directly supports the report's treatment of device-dependent sub-synchronous oscillations (SSTI/SSO) and provides a recognised reference for recommended study workflows in converter-rich power systems relevant to the evolving Nordic grid.

2.5.2 Typical Mitigation and Protection Methods

Effective management of torsional interaction phenomena requires a combination of unit-side protection, system-side damping measures, and evidence-driven monitoring and analysis. Historically, mitigation focused primarily on classic SSR arising from series-compensated lines, but the evolving Nordic power system, with increasing penetration of HVDC and inverter-based resources, has introduced new excitation pathways that call for a broader and more coordinated approach.

Modern mitigation strategies therefore span from protective relays that act directly on the turbine–generator shaft, to grid-level devices and control schemes that modify the electrical environment, and finally advanced diagnostic and modelling tools that provide insight into emerging risks and support adaptive decision-making.

The methods summarized below represent the state of practice in industry literature, OEM recommendations, and recent Energiforsk and international studies. Each measure addresses different parts of the electromechanical chain, and no single method is sufficient on its own. Instead, robust protection is achieved through a layered defence, where unit-side and system-side measures are complemented by high-quality monitoring, data sharing, and systematic study workflows.

Recent ENTSO-E incident learning (Section 2.5.3) also emphasises that validated and coordinated protection settings (including time delays and measurement-location considerations), together with high-quality disturbance recordings and efficient data exchange, are prerequisites for avoiding unintended disconnections and for enabling credible post-event learning. These factors also influence the mechanical duty cycle experienced by turbine–generator shafts.

Table 2-1 provides an overview of the most referenced mitigation and protection methods and how they map to the three functional categories used in this report: (i) Unit-side (measures implemented directly on the turbine–generator set), (ii) System-side (measures implemented in the transmission grid or converter controls), and (iii) Evidence & feedback (methods that enhance observability, model accuracy, or post-event learning). For clarity, the mitigation and protection methods discussed below are grouped according to these categories.

As agreed in the reference group, the emphasis of this report is the nuclear power plant perspective. For that reason, unit-side measures that plant owners and operators can implement directly (protection, monitoring, recording, and event-response routines) are described more explicitly than system-side measures, which are largely under TSO or vendor control and are therefore treated at an overview level.

- SSR protection and operational routines:
    - Scope: Dedicated SSR/torsional protection is intended to detect sub-synchronous electrical components and associated torsional response early enough to limit cyclic shaft stress and fatigue accumulation.
    - Measurements and detection: Implementations typically use generator electrical quantities (e.g., stator currents/voltages) with frequency-selective processing (filtering) to identify sub-synchronous components near mechanically relevant mode frequencies and to discriminate against normal operating harmonics and transient noise.
    - Example: Some installations use dedicated SSR functions (e.g., ABB) with signal processing to detect sub-synchronous components and associated oscillations.

- Alarm/trip philosophy: Depending on plant philosophy, the function can be configured for staged response (alarm and operator action) and/or automatic trip when thresholds are exceeded for a defined duration.
- Interface to generator protection: Where SSR protection trips the generator breaker, trip logic, time delays, and interlocks should be coordinated with other generator and grid protections to avoid unnecessary disconnections.
- Settings, validation, and lifecycle: Setpoints should be based on unit-specific shaft data (mode frequencies and, where possible, damping/stress limits) and validated against studies (screening and EMT) and/or event recordings. Configuration control and periodic functional tests are needed, particularly after major grid or plant changes.
- Event recording and follow-up: Alarm or trip should trigger saving of relevant waveforms (electrical oscillography and, where available, mechanical/vibration channels) to enable correlation with the initiating grid event and subsequent frequency-domain analysis.
- Limitations: SSR protection is not a substitute for systematic studies and does not by itself quantify cumulative fatigue from repeated non-tripping events. False operations can occur if inputs are noisy or thresholds are not tuned; event records and root-cause review routines are therefore important.

- Excitation system control (PSS, active damping):
    - Scope: Generator excitation control (AVR with power system stabiliser, PSS) is primarily designed to improve low-frequency electromechanical damping (typically rotor-angle modes) by modulating excitation in response to measured speed/power/voltage signals.
    - Relevance to torsional interaction: While PSS is not a dedicated torsional protection function, excitation-system dynamics can influence the electrical torque seen by the generator and can therefore affect damping of certain oscillatory phenomena. Some applications also implement supplementary damping controls ("active damping") aimed at specific interaction frequencies.
    - Practical constraints: Torsional modes of turbine–generator shafts are typically at higher frequencies than classic PSS targets. Any design or retuning intended to influence sub-synchronous ranges must therefore be treated as unit-specific and coordinated with the OEM to avoid adverse interactions or unintended amplification.
    - Verification and follow-up: Changes to excitation control (including PSS tuning) should be validated against unit models

and, where possible, measurements (e.g., ring-down tests, disturbance recordings). Event recordings and post-event analysis remain important to confirm that the intended damping effect is achieved under relevant operating conditions.

- Monitoring and measurement (electrical and mechanical):
    - Purpose: Improve observability of grid-induced mechanical duty by capturing electrical disturbance signatures and the corresponding unit response, enabling event attribution, trending, and evidence-based follow-up.
    - Electrical recording: Ensure that disturbance recorders and relay oscillography capture generator terminal quantities (voltage, current, frequency proxies) with sufficient sampling rate and appropriate trigger logic for faults, switching, and oscillatory events; recordings should be retained long enough to support post-event analysis and cross-correlation with external event timelines.
    - Mechanical monitoring: Where feasible, add dedicated torsional measurements (e.g., torsional strain/torque proxies or torsional vibration sensors) to detect sub-synchronous components and weakly damped responses that may not be visible in standard lateral vibration monitoring. Where direct torsional measurement is not available, ensure that existing vibration and condition-monitoring channels (e.g., bearing vibration, shaft displacement, coupling indicators) are configured to support disturbance-related investigations. In practice, this should include reviewing sensor bandwidth and sampling rates, ensuring that relevant vibration and shaft-displacement channels are included in event-triggered recording, time-synchronising these records with electrical disturbance recordings, and defining routines for frequency-domain review after significant grid events.
    - Time synchronisation: Use a common time base (e.g., GPS/NTP/PTP) across electrical recorders, protection systems, and plant monitoring systems to enable credible sequence reconstruction and comparison with external measurements (where available).
    - Data handling and routines: Establish clear routines for archiving, quick-look screening (time and frequency domain), and escalation criteria for detailed review. For recurring non-tripping events, trend relevant indicators over time (e.g., sub-synchronous content, vibration response levels, event counts) to support maintenance planning and model updates.
    - Limitations: Limited sensor bandwidth, insufficient sampling rate, or missing time synchronisation can make sub-synchronous content difficult to detect and can reduce confidence in attribution.

Monitoring should therefore be complemented by studies and by periodic review of measurement settings as grid conditions and unit configurations change.

Table 2-1. Mitigation and protection methods

Method	Primary function	Category
SSR/Torsional Stress Relays	*Detect torsional oscillations; alarm/trip to prevent mechanical damage*	*Unit-side*
System Studies & Screening	*Identify exposure (SSR/SSTI/SSO) via frequency scans, eigenvalue analysis, EMT studies*	*System-side / Evidence*
FACTS & Dynamic Stabilizers (SVC, STATCOM, TCSC, damping controllers)	*Provide electrical damping; reduce risk of SSR/SSTI/SSO*	*System-side*
Advanced Monitoring (PMU, digital twin, high-speed data acquisition)	*Observe torsional modes and damping; support diagnostics and prediction*	*Evidence & feedback*
Plant-side monitoring and recording (electrical and mechanical)	*Capture event waveforms and unit response (oscillography, vibration/torsion) to support attribution, trending, and follow-up*	*Unit-side / Evidence*
Excitation System Control (PSS, active damping)	Add torsional or electromechanical damping through excitation control	Unit-side

These measures typically work best in combination: unit-side protection prevents excessive mechanical stress, system-side damping reduces the likelihood of sustained sub-synchronous oscillations, and evidence-driven monitoring ensures that emerging risks are detected early and that models and settings remain valid as the Nordic grid evolves.

2.5.3 Summary of findings from literature

From the literature, several practical measures are identified that NPPs can implement or strengthen to reduce mechanical risks to turbine–generator shafts:

- Enhance shaft-side protection:
  Ensure that SSR/torsional stress relays are installed, properly configured, and regularly tested. These relays can detect dangerous oscillations and trigger alarms or trips before mechanical damage occurs.
- Improve monitoring and observability:
  Invest in high-resolution vibration monitoring (including torsional vibration if possible) and ensure that event-triggered recordings are available for post-event analysis. Plants with better observability can

detect non-obvious risks and justify operational decisions more confidently.

- Strengthen post-event analysis routines:
  Develop systematic procedures for reviewing grid disturbances and correlating electrical events with mechanical responses. Use spectrum analysis and event logs to identify trends and potential fatigue accumulation.
- Coordinate with TSOs and OEMs:
  Establish regular data exchange and joint event reviews with the TSO and OEMs. Access to PMU data and wide-area measurements can help reconstruct events and improve learning from disturbances.
- Maintain and update shaft models:
  Periodically validate shaft dynamic parameters (natural frequencies, damping) using measurements or updated studies, especially after major upgrades or changes in operating conditions.
- Adopt conservative operational practices where observability is limited:
  If direct torsional monitoring is not available, apply more conservative protection settings and operational margins, and rely on studies and external data to justify risk acceptance.
- Participate in collaborative learning:
  Engage in reference group activities and share anonymized findings to build stronger evidence base and harmonize risk management practices across Nordic NPPs.

NPPs can reduce mechanical risks by combining robust protection, improved monitoring, systematic analysis, and active collaboration with TSOs and OEMs. Plants with higher observability and stronger routines can manage some risks through detection and response, while others may need to rely on conservative margins and external studies.

While the literature provides a solid foundation of risks and mitigation strategies, the Nordic power system is evolving rapidly. The following section outlines recent developments, such as lower inertia and more HVDC connections, that form today’s context for these vibration phenomena and influence how stakeholder input is interpreted.

2.6 RECENT DEVELOPMENTS IN THE NORDIC POWER SYSTEM

The Nordic power system is undergoing a rapid and far-reaching transformation driven by the retirement of thermal generation, large-scale integration of renewable power, and increased use of power-electronic interfaces such as HVDC links and inverter-based resources (IBR). These developments have a direct impact on the electromechanical environment in which large synchronous generators operate and therefore affect the likelihood and severity of torsional interaction phenomena.

Recent developments and operational context (qualitative):

- The Nordic power system is experiencing rapid changes, including the retirement of synchronous units, commissioning of large offshore wind clusters, and increased reliance on HVDC links. These developments alter both the frequency and character of disturbances experienced by nuclear power plants (Energiforsk, 2021:835; Energiforsk, 2025:1091).
- Weak-grid conditions (low short-circuit strength) and reduced inertia increase vulnerability to disturbances and can amplify the mechanical duty cycle on turbine-generator shafts (Energiforsk, 2025:1091; Energiforsk, 2025:1145).
- High-load operation increases baseline torque and mechanical stress in the shaft line and can reduce operational margin. The concern is not that full-power operation is inherently problematic, but that a rapid active-power reduction from full load may impose fast torque and thermal/load changes on the turbine–generator train while operational headroom is limited. As a result, similar grid disturbances may translate into higher mechanical duty than under partial-load operation, depending on unit design, steam conditions, ramp rate, and the disturbance sequence.
- HVDC links and offshore wind are cited as exposure drivers for disturbance patterns, with stakeholders noting that incidents or operational regimes associated with these technologies can increase the likelihood of repeated switching and non-stationary operating conditions (ENTSO-E, 2017; CIGRE, 2014).
- Several interviewees noted that fault exposure may be higher during summer due to more frequent lightning, which can increase the frequency of grid faults and associated mechanical effects. This observation is qualitative and reflects stakeholder experience rather than a quantified analysis in this report.
- Some interviewees highlighted that steam conditions and loading can contribute to damping of certain torsional responses, and that this may reduce vibration severity compared with low-load conditions. This observation is qualitative and depends on unit design and operating state.

2.6.1 Lower inertia and higher RoCoF

The synchronous inertia of the Nordic system is increasingly situation-dependent. Retirements and reduced dispatch of synchronous units can lower inertia in many operating situations, while new large synchronous units such as Olkiluoto 3 have also added inertia and can offset this in other periods. In practice, the key change is a shift in the distribution and availability of inertia over time: low-inertia conditions can occur during maintenance outages of large synchronous units (e.g. NPP revisions) and during periods of low hydropower production combined with high shares of inverter-based resources (IBR) and HVDC imports. Lower inertia results in faster frequency dynamics and higher rates of change of frequency (RoCoF) during disturbances. For turbine–generator shafts, this can increase the magnitude and speed of torque transients, amplify the mechanical duty cycle, and potentially contribute to fatigue accumulation. These effects are particularly relevant for nuclear units, which typically operate at high load and have limited flexibility to provide fast active-power response (Energiforsk, 2025:1091; Energiforsk, 2025:1145; Energiforsk, 2025:1083).

2.6.2 Increasing reliance on HVDC and power-electronics-dominated interfaces

The Nordic grid now contains numerous HVDC interconnectors (LCC and MMC/VSC) and continues to add large inverter-based resource (IBR) installations. These technologies introduce converter-driven control dynamics that can interact with synchronous machines at sub-synchronous frequencies. Depending on grid strength and operating conditions, HVDC and IBR control loops may reduce torsional damping or, in rare cases, introduce negative damping, thereby increasing the risk of SSTI or broader sub-synchronous oscillations (SSO) (ENTSO-E, 2017; CIGRE, 2014). This represents a fundamental shift compared with the historically dominant SSR phenomenon, which was primarily associated with series-compensated AC lines.

2.6.3 Recent European learning: ENTSO-E final report on the Iberian blackout

The ENTSO-E Expert Panel final report on the grid incident in Spain and Portugal on 28 April 2025 provides recent European learning that is relevant to this report's focus on how grid disturbances can create mechanical duty (torque transients, torsional excitation, and vibration-related stress) in large synchronous units (ENTSO-E, 2026). While the Iberian incident is not primarily presented as a turbine-shaft torsional event, it illustrates how voltage behaviour, oscillations, and protection and disconnection practices, especially for inverter-based resources and embedded generation, can rapidly shape system trajectories and disturbance severity. For Nordic nuclear power plants, the relevance is primarily indirect: such sequences can increase the likelihood of repeated switching and non-stationary operating conditions and can complicate post-event learning unless monitoring and data exchange are robust.

- Converter-driven oscillatory phenomena can co-exist with broader system dynamics. ENTSO-E identifies a forced oscillation around 0.63 Hz and classifies it as plausibly within the family of converter-driven stability phenomena, with correlation to reactive power exchange; the report also discusses other oscillatory behaviour preceding the blackout. Even when oscillations are outside typical torsional mode ranges, they indicate weakly damped dynamic interactions and control sensitivity that can coincide with fast voltage changes and switching sequences that generate electromagnetic torque transients in synchronous machines.
- Overvoltage and protection behaviour can drive large and fast disconnection sequences. The report describes a sequence of generation disconnections and highlights that over/undervoltage protection settings and behaviour should be validated against withstand requirements, including attention to measurement location, hysteresis, and time-delay coordination. Protection behaviour matters to mechanical risk because avoidable trips and reconfigurations can increase the number of

disturbances 'hits' and create repeated torque impulses rather than a single contained event.

- Embedded PV behaviour can be both influential and difficult to observe. ENTSO-E notes that distribution-connected PV disconnections contributed materially to the loss of generation and emphasises that non-observable embedded generators introduce uncertainty in system response. For a Nordic context, this reinforces that embedded generation behaviour (a subset of IBR) can affect escalation pathways and the disturbance spectrum seen by nearby synchronous units.
- Dynamic monitoring, oscillation detection, and data exchange are prerequisites for learning. ENTSO-E recommends strengthened use of PMUs, oscillographs, and operational oscillation detection tools, and improved data exchange to enable efficient event reconstruction. This aligns with this report's emphasis on correlating plant-side indications (e.g., vibration trends, protection logs, and torsional proxies where available) with TSO measurements to support credible post-event learning.
- Routine post-event controls should be learning-oriented. ENTSO-E recommends regular controls after trips/unexpected disconnections to verify that behaviour is consistent with withstand capability requirements. For the mechanical focus of this report, an analogous learning is to formalise a joint event learning loop (TSO + plant owner + OEM) so that significant events lead to timely reconstruction, attribution, and (where justified) updates to settings, procedures, and study models.

Overall, the ENTSO-E Iberian investigation reinforces two cross-cutting messages relevant to Nordic NPP mechanical risk management: (i) voltage behaviour and converter-driven dynamics can be central in incident escalation and may influence the disturbance patterns experienced by synchronous units, and (ii) evidence quality (high-resolution monitoring, oscillography, and data exchange) is decisive for credible post-event learning and for maintaining alignment between withstand expectations, protection settings, and operational practices. These themes are carried forward in Sections 4–5, where the analysis and recommendations address both technical risk drivers and practical monitoring/procedure improvements.

2.6.4 Changing power-flow corridors and system topology

Large north-to-south energy transfers increased cross-border trade, and new offshore connections are redistributing power flows across the Nordic grid. This alters the effective electrical distance between nuclear units and potential sources of excitation such as series-compensated corridors, HVDC terminals, or major IBR clusters. As a result, SSR or SSTI risk paths may appear only under certain topologies, for example during maintenance outages, line switching, or unusual market-driven flow patterns. The intermittency of these conditions reinforces the need for systematic screening studies and scenario-based EMT analysis rather than relying solely on static, nominal-grid assessments.

2.6.5 Implications for this study

Together, these recent developments in the Nordic system imply that turbine–generator shafts in the nuclear power plants may be exposed to disturbance characteristics that differ significantly from historical experience. Faster dynamics, greater variability in grid strength, and increased prevalence of converter-dominated interactions highlight the importance of combining traditional SSR assessments with analyses tailored to SSTI and IBR-driven SSO. They also underscore the value of enhanced monitoring, data exchange with TSOs, and updated operational guidelines that reflect the evolving behaviour of the Nordic system.

3 Stakeholder Interviews

To ground the technical findings in practice, this chapter presents insights from stakeholders (nuclear plant operators) gathered through interviews.

3.1 METHODOLOGY FOR INTERVIEWS

Interviews were conducted with representatives from the Nordic nuclear power plant operators. The interviews followed a structured questionnaire designed to collect experience-based, qualitative input on grid-induced mechanical effects on turbine–generator systems. The questions were open-ended and formulated to avoid leading the interviewees toward predefined conclusions.

The questionnaire was organised into a set of thematic sections (A–H). An initial section addressed the interviewee's background and professional role, providing context for the interpretation of responses. This was followed by questions focusing on practical experience with grid events and their observed mechanical effects, including the types of disturbances considered most relevant and the operating conditions under which sensitivity is perceived to be highest.

Subsequent sections addressed torsional vibrations and shaft dynamics, with emphasis on how such phenomena are assessed and managed in practice, the availability of shaft dynamic data, and whether torsional behaviour has been linked to maintenance findings, alarms, or operational constraints. Specific attention was also given to sub-synchronous phenomena, including sub-synchronous resonance and other forms of torsional interaction, in order to capture the interviewees' awareness of these issues and their confidence in existing analysis approaches under evolving grid conditions.

Further sections covered monitoring, protection, and data availability, with the aim of understanding what information is currently available to detect and analyse grid-induced mechanical effects, as well as how data is shared and used across organisational boundaries. Mitigation measures and operational practices were then discussed to identify how such risks are managed in practice and to highlight potential trade-offs between mechanical protection, availability, and operational flexibility.

Use of AI-generated schematic figures: Where schematic figures are labelled as AI-generated, they were created using Microsoft 365 Copilot based on user-provided prompts describing the intended technical concept. These figures are included to support qualitative explanation and readability, and they are not intended to represent unit-specific designs, parameter values, or validated simulation results. Technical statements, conclusions, and recommendations in the report are based on the cited literature and stakeholder input; the figures should be interpreted as conceptual illustrations only.

Finally, the questionnaire included forward-looking questions on how interviewees expect grid-induced mechanical risks to evolve over time, given ongoing changes in the power system, and invited recommendations regarding future studies, guidelines, or coordination measures. The full interview questionnaire, together with a brief rationale for each question, is provided in the appendix.

After completing the interviews, this report synthesises the main themes and differences in the stakeholder responses in the next section.

3.2 SUMMARY OF STAKEHOLDER INPUT

This section summarises the stakeholder input collected through the interview campaign, covering perspectives from nuclear power plant operators. The intent is to capture practical experience, current practices, and perceived risk drivers related to grid-induced mechanical effects, while maintaining a neutral tone and avoiding attribution of specific statements to individual sites. The section first clarifies limitations and interpretation of the interview evidence (Section 3.2.1) and then compares NPP responses on an anonymised basis (Section 3.2.2). TSO and OEM perspectives are addressed primarily through the consolidated field insights and the comparison with literature in Sections 3.3–3.4.

3.2.1 Limits and interpretation of interview evidence

The interview responses provide experience-based input and are valuable for identifying themes, perceived risk drivers, and practical constraints. However, the material should be interpreted with care, since differences in roles, instrumentation, and organisational routines can lead to different levels of detail and different conclusions even when the underlying exposure is similar.

- Role- and interface-dependence: Responses reflect each interviewee's responsibilities (mechanical, electrical, operations, maintenance) and their typical interfaces with the TSO and OEMs; the same event may therefore be described differently depending on organisational viewpoint.
- Observability limits: The ability to detect and characterise torsional/sub-synchronous behaviour varies with measurement capability (sensor coverage, sampling rate, triggering/recording). Plants without direct torsional measurements may rely on indirect indicators (e.g., lateral vibration trends, inspection findings), which affects both confidence and level of detail.
- Absence of reported effects is not proof of absence: A 'no observed impact' response can reflect limited measurement sensitivity, infrequent triggering of post-event reviews, or lack of clear attribution pathways—not necessarily a lower underlying exposure.
- Recall and reporting bias: Perceived changes over time may be influenced by changes in monitoring, increased awareness, changes in event reporting practices, and the presence of recent major disturbances.
- Heterogeneity of units and time periods: Units differ in shaft design, protection philosophy, and refurbishment history; interviewees may also

reference different time windows, which limits direct comparability across responses.

- Quantification limitations: The interviews were not designed to quantify fatigue damage or event frequency statistically. Where lifetime impact is discussed, it should be read as expert judgement unless supported by dedicated measurements, studies, or maintenance evidence.

Credibility statement: The interview material is considered credible as qualitative evidence of perceived risk drivers, current practices, and operational constraints across stakeholders. It is not, on its own, sufficient to quantify event frequency, mechanical duty cycles, or fatigue life impact. In this report, interview findings are therefore used primarily to (i) identify and prioritise mechanisms and scenarios for further technical assessment, and (ii) interpret why stakeholders may reach different practical conclusions, while quantitative claims are reserved for cases supported by measurements, studies, or documented maintenance evidence.

3.2.2 Cross-plant comparison of NPP responses

This section synthesises responses from multiple Nordic nuclear power plant stakeholders to the mechanical risk survey on vibrations and grid events. The purpose is to highlight common themes, differences in assessment and practice, and plausible reasons for those differences. To support open learning while respecting confidentiality, the discussion is intentionally anonymised and does not attribute statements to any specific plant or individual.

Similarities across responses

- Most interviewees reported having observed at least some mechanical manifestation following grid disturbances (e.g., short-term vibration changes, coupling displacement indicators, or findings in couplings/sleeves during inspection/overhaul). At the same time, at least one stakeholder reported no clear coupling between disturbances and damage, describing the observed effects primarily as vibration changes comparable to other operational variations.
- Sub-synchronous phenomena (SSR/SSO, and more broadly converter-driven interactions) were repeatedly described as a potentially high-consequence category due to their ability to persist or to be less visible without dedicated monitoring/protection.
- Several interviewees described weak-grid conditions and operation at high active-power output, i.e. high generator load close to rated output, as situations that can increase vulnerability or the perceived mechanical impact of similar electrical events.
- A recurring uncertainty is whether observed transient torsional and vibration responses translate into measurable life reduction (fatigue accumulation) versus being mainly short-term excursions without long-term consequence.

- Interviewees expressed broad interest in improved measurement and observability, as well as closer coordination between plant organisations and TSOs, to better understand event characteristics and enable consistent post-event learning.

Section 3.4 of this report compares these interview-based observations with published mechanisms and prior studies (e.g., EPRI, 2006; Energiforsk, 2016:295; Energiforsk, 2017:355; Energiforsk, 2020:707).

Key differences in the responses

- Monitoring and protection capability differs significantly. Some respondents described dedicated arrangements to detect torsional/sub-synchronous phenomena and to record events, while others stated that they do not measure torsional vibration (or only do limited/periodic measurements). This difference directly affects what can be concluded from experience: plants with higher observability (i.e., the ability to measure/record relevant torsional response with sufficient detail and relate it to events) can describe event signatures and variability in more detail, whereas plants with limited observability may rely on indirect indicators (e.g., lateral vibration trends, inspection findings) or may conclude that no clear link has been established.

- Post-event analysis practices range from systematic to ad hoc. Some interviewees described routine recording and analysis triggered by events exceeding thresholds, while others described limited post-event processing, especially where no direct torsional measurements exist or where organisational routines are still developing.

- Electrical observability (power-quality and event characterisation) is uneven. Some interviewees noted that they do not currently monitor power quality in a way that supports detailed frequency-domain interpretation of disturbances, while also describing plans to expand instrumentation to include both torsional measurements and improved electrical recording. This affects the ability to classify events (e.g., distinguishing short transient faults from oscillatory phenomena) and to connect electrical signatures to mechanical response.

- Perceived trend in external grid disturbances is not uniform. Several respondents expressed that disturbances have become more frequent and/or receive more attention than before. Others reported no clear trend in their collected data. A third pattern is uncertainty due to lack of statistics or changing detection sensitivity over time.

- Confidence in shaft-dynamic parameters varies by unit and parameter type. Natural frequencies and mode shapes were generally described as available, while damping was consistently described as more uncertain. This is consistent with the literature, which notes that damping is difficult to validate and often requires measurement-based calibration to reduce uncertainty (EPRI, 2006; Energiforsk, 2016:295).

- Different emphasis on what is ‘most critical’. While SSR/SSO is frequently highlighted as high risk, other answers emphasised more general rotor-angle stability during faults/switching or pointed to future risks from converter-driven interactions as a key concern.

- Understanding of ‘where the stress concentrates’ differs and is event-dependent. Some responses emphasised that short-circuit events on the grid versus internal generator faults may manifest differently and that the location of highest mechanical impact is not necessarily intuitive. The same unit can also have mechanically critical sections that are more exposed under certain excitation patterns (e.g., specific couplings/shaft spans), which may help explain why similar electrical events are not always associated with the same mechanical indicators.

- SSR protection and interpretation. Some units rely primarily on SSR protection. Protection operations (alarm or trip) can indicate the presence of transient sub-synchronous components following grid events, but interpretation is not always straightforward, especially where no direct torsional measurement or sufficient event recordings are available.

- Events fade and spectrum analysis is used. Some interviewees reported that oscillatory responses usually fade and that spectrum analysis is used to interpret them.

- Vector changes during disturbances and mechanical checks during revision. Some interviewees observed vector changes during major disturbances and perform mechanical checks during revision, but find it difficult to link mechanical findings to specific events.

What differed, and why it matters: Across the responses, the most consequential differences were not in whether sub-synchronous phenomena are recognised as potentially high consequence, but in (i) how directly the mechanical response can be observed, (ii) how systematically events are reviewed after they occur, and (iii) how confidently unit-specific shaft data (especially damping) is considered representative for today’s conditions. These differences matter because they shape the strength of the evidence base behind operational choices: where observability and routines are strong, plants can more readily relate grid events to mechanical response and use that feedback to tune protection and procedures; where they are weaker, similar exposure may be managed through more conservative margins, greater reliance on studies, and stronger dependency on external data from TSOs and OEMs.

Possible reasons for differences

- **Electrical environment and exposure.** Differences in grid topology, proximity to series-compensated corridors, local short-circuit strength, and the mix of nearby power-electronic devices can change both the likelihood and the character of mechanically relevant disturbances.

- **Recent system changes and infrastructure events.** Stakeholders linked changes in experienced disturbance patterns to recent network reconfiguration and generation mix changes (e.g., retirement of nearby synchronous units, commissioning of large offshore wind clusters, and incidents or operational regimes associated with HVDC links). Such changes can alter both exposure (how often disturbances are 'felt') and sensitivity (effective grid strength and damping seen by the unit).

- **Unit design and shaft-line characteristics.** Turbine-generator configurations, coupling designs, torsional mode frequencies, and damping characteristics differ by unit, which can make the same external disturbance more (or less) effective at exciting critical torsional modes.
- **Instrumentation and data availability.** Plants with dedicated torsional monitoring and higher-resolution recording can detect and classify events that would otherwise remain 'invisible' or be interpreted only through indirect maintenance findings. Conversely, limited sampling rates or limited sensor coverage can constrain what can be inferred even when measurements exist.
- **Protection philosophy and operational procedures.** Differences in whether actions are manual vs automatic, alarm vs trip thresholds, and how operators are instructed to respond will affect both observed outcomes (e.g., prevented escalation) and how events are perceived.
- **Learning loops and organisational interfaces.** The maturity of post-event routines and the degree of routine coordination with the TSO (e.g., data exchange, joint disturbance reviews, study updates) can drive differences in awareness and confidence in conclusions.
- **Time period and 'attention bias'.** Some respondents explicitly noted that events may appear more frequent because they are monitored more closely today, or because reporting practices have changed following major upgrades.
- **Perceived increased sensitivity, possibly due to better detection, not fragility.** Some stakeholders feel their plants are more sensitive today, but this may reflect improved detection rather than increased fragility or renewed focus on grid interactions.

Discussion: Dedicated torsional vibration measurements and their role in exemptions and risk management

Responses indicate that at least one Nordic unit has implemented dedicated torsional vibration measurement capability (including recording and analysis functionality), while several other units describe limited or no direct torsional measurements. This asymmetry can influence both the ability to justify certain operational exemptions (e.g., accepting exposure under defined conditions) and the strength of the evidence base for risk decisions. The survey responses suggest that exemptions may be easier to justify when a plant has high observability of torsional behaviour and can credibly detect sub-synchronous stress early, whereas plants without such observability may apply more conservative operational rules or rely more on indirect indicators and studies.

Potential advantages

- Early detection of high-consequence phenomena. Dedicated torsional measurements can reveal sustained or weakly damped oscillations that may not be visible in standard vibration monitoring.
- Better event attribution and learning. Time-domain and frequency-domain recordings enable correlation of mechanical response with grid events and support joint investigations with TSOs.
- Improved confidence in risk decisions. Direct measurement can reduce reliance on assumptions about damping and on generic shaft models, enabling more evidence-based operational constraints and protection settings.
- Support for model validation. Measurements can be used to validate torsional models and to calibrate digital-twin or screening approaches, improving predictive value over time.

Potential disadvantages and limitations

- Complexity and lifecycle cost. Instrumentation, calibration, maintenance, and obsolescence management can be non-trivial, especially if the solution is vendor specific.
- Interpretation burden. Raw torsional signals may require expertise, robust thresholds, and clear procedures to avoid false alarms or inconsistent operational responses.
- Coverage limitations. Measurements may be available only at selected shaft locations or for selected modes and may not capture all relevant coupled phenomena (e.g., interactions involving blades or non-measured sections).
- Data-handling constraints. High-resolution measurements can create challenges for data storage, cybersecurity, and integration with existing plant monitoring and event review processes.

Overall, the differences in monitoring capability appear to be a key explanatory factor behind differences in confidence, in the level of detail in responses, and in how plants describe acceptable operating practices. For the purpose of this report, these findings can be framed as an ‘observability gap’ rather than a difference in safety intent: plants with higher observability can manage some risks through detection-and-response, while plants with lower observability tend to manage the same risks through conservatism, reliance on studies, and coordination with the TSO.

It is increasingly recognized that disturbances which do not result in trips or immediate alarms may still contribute significantly to long-term mechanical duty and fatigue accumulation in turbine-generator systems. These events, often moderate but repeated, can go unnoticed and lead to sudden failures if not properly monitored and analysed. The approach described in this report reflects the steering group’s intent to prioritize detection and understanding of such ‘non-obvious' risks, ensuring that operational routines and monitoring strategies are designed to catch them before they escalate into critical incidents.

Takeaway: The responses show broad alignment on what can be high consequence (especially sub-synchronous behaviour) but differing levels of confidence and detail, largely driven by differences in measurement capability, post-event routines, and reliance on external studies/data. This helps explain why similar issues may be managed with different levels of operational conservatism across plants without implying different safety intent.

To illustrate these themes, the following section highlights a few concrete field examples and reference group reflections.

3.3 KEY INSIGHTS AND EXPERIENCES FROM THE FIELD

Practical field observations mirror key insights. Some plants have reported minor coupling deformations, transient vibration spikes, and occasional SSR relay trips after grid events (see Section 4.3 for details on these examples).

3.3.1 Reference group reflections

The reference group discussed a recent example of low-frequency active-power oscillations observed in grid-side measurements (approximately 1.4 Hz), with variations on the order of ±10 MW in one unit after mean-value removal. The group considered the observation technically relevant, including the possibility that grid-side measurements can reveal electromechanical modes that are not readily visible in existing plant-internal mechanical monitoring. At the same time, the discussion underlined that it is currently difficult for several plants to confirm how often similar oscillations occur in normal operation, since routine measurement and archiving of suitable electrical waveforms (or equivalent high-resolution indicators) is limited.

A recurring theme was an 'observability gap': several stakeholders noted that they primarily rely on protection-system records and event-triggered data, with limited systematic measurement during normal operation. The group also highlighted that dedicated SSR protection is typically used as a protection function (alarm/trip) rather than as an operational measurement and learning tool, which limits the ability to trend sub-synchronous exposure over time and to build a consistent evidence base for root-cause analysis and mitigation.

The reference group agreed that improved correlation of electrical measurements (frequency content and event signatures) with plant-side information (vibration trends, protection logs, and mechanical inspection findings where available) is a key enabler for credible learning. The group further noted that wide-area measurements (e.g., PMUs) can support detection of low-frequency oscillations and help reconstruct disturbance sequences, but that additional measurement approaches are needed to capture higher-frequency sub-synchronous components relevant for classical SSR (ENTSO-E, 2026; CIGRE, 2014).

Finally, the discussion reinforced that sustained or poorly damped events can occur during specific system conditions (e.g., testing scenarios) and that coordinated procedures and data exchange between plants and TSOs are important to prevent recurrence and to support rapid post-event learning.

Finally, Section 3.4 of this report compares these field insights with the literature to identify alignments and gaps.

3.4 COMPARISON WITH LITERATURE FINDINGS

This section compares the interview and reference-group input with published findings to identify alignments, differences, and practical implications. Overall, the field experience aligns with key themes in the literature and underscores the need to adapt recommendations to local measurement capability, operational routines, and organisational interfaces.

Stakeholder interviews confirm that sub-synchronous phenomena (SSR, SSTI, SSO) are recognized as potentially high-consequence risks, consistent with the literature (EPRI, 2006; Energiforsk, 2017:355; CIGRE, 2014). However, the ability to detect and characterize these events varies significantly across plants, depending on instrumentation, measurement routines, and post-event analysis practices.

While the literature emphasizes systematic screening, advanced monitoring, and coordinated learning with TSOs and OEMs, practical experience reveals that some NPPs rely primarily on indirect indicators or conservative operational margins due to limited measurement capability (Energiforsk, 2016:295; ENTSO-E, 2026). This "observability gap" shapes how risks are managed: detection and response where measurement is strong, conservatism and reliance on external studies where it is not.

Both the stakeholder input in this project and the reviewed literature indicate that early detection of non-obvious risks, routine review of disturbance events, and transparent coordination across organisational boundaries are important for maintaining safe operation (EPRI, 2006; Energiforsk, 2016:295; ENTSO-E, 2026). The field experience summarised in Chapter 3 reinforces these recommendations and underlines the need to adapt mitigation strategies to local conditions, while continuously improving measurement and analysis capability.

4 Analysis of Risk Factors and Existing Solutions

Chapter 0 builds on the technical findings (Chapter 1.5) and stakeholder input (Chapter 3) to identify where mechanical risks are most significant and how well current solutions address them. Specifically, the analysis first pinpoints key risk factors (Section 4.1), then evaluates monitoring and protection solutions (Section 4.2) and illustrates findings with practical examples (Section 4.3). Finally, the chapter delivers recommendations (Section 4.4) and highlights improvement opportunities (Section 4.5), ensuring the report's conclusions are grounded in both theory and practice.

4.1 KEY RISK FACTORS

Mechanical risk to a nuclear unit's turbine–generator shaft depends on both the grid disturbance characteristics and the unit's operating context. High-impact electrical events, for example, a short-circuit fault or out-of-phase switching very close to the unit, impose larger torsional stress than remote or minor disturbances (EPRI, 2006; Siemens PTI, 2018). Likewise, weak-grid conditions (low system inertia or low short-circuit strength at the unit's connection point) amplify a disturbance's effect: faster frequency swings and less inherent damping mean the same fault causes greater torque transients (Energiforsk, 2025:1091; Energiforsk, 2025:1145). The presence of series compensation or fast power-electronic controls nearby (such as an HVDC link or a large inverter-based resource) is another risk factor, as these can excite sub-synchronous oscillations beyond the typical transient torque from a fault (CIGRE, 2014; ENTSO-E, 2017).

On the plant side, operating conditions and shaft dynamics determine how vulnerable the unit is. A generator running at high active-power output has higher baseline torque in the turbine–generator shaft line. A rapid active-power change from such a high-load operating point may therefore impose a larger incremental mechanical duty than a similar change from partial load, depending on unit design, steam conditions, ramp rate, and the disturbance sequence (EPRI, 2006; Energiforsk, 2016:295). Units also differ in their torsional mode frequencies and damping. A shaft with a lightly damped mode that coincides with the disturbance frequency will experience stronger, more sustained vibrations, while damping remains one of the more uncertain parameters in practice (EPRI, 2006; Energiforsk, 2016:295). In short, the worst-case mechanical duty occurs when an aggressive disturbance (severe, close-in, or repeated) meets an unfavourable unit state (weak grid, heavy load, and a shaft mode prone to excitation). Conversely, under more favourable conditions (strong grid, moderate load, well-damped modes), the same disturbance is far less threatening.

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4.2 EVALUATION OF EXISTING MONITORING AND PROTECTION SOLUTIONS

In line with recent ENTSO-E incident investigations (see Section 2.5.3), this evaluation goes beyond checking if monitoring and protection functions exist – it asks whether they provide sufficient evidence quality for event reconstruction and learning. Key factors include measurement bandwidth, time synchronization, trigger/record settings, and the availability of supporting TSO data (e.g. PMU feeds, relay oscillography). This perspective is crucial because limited observability can lead to differing conclusions about a unit's exposure and can delay necessary adjustments to settings, procedures, or models.

Monitoring and evidence:

- Stakeholders express a strong interest in using PMU (Phasor Measurement Unit) data for analysis and event correlation, highlighting the value of high-resolution, time-synchronized measurements for reconstructing disturbance sequences and linking electrical events to mechanical response (ENTSO-E, 2026).
- Several interviewees stated that they have measurement data available that can be used to verify calculated values, which supports more robust risk assessment and model validation.
- Some interviewees noted that collaboration with universities is planned to strengthen SSR and torsional analysis methods and interpretation of vibration phenomena.
- Several interviewees stated that spectrum analysis is used to interpret events and assess the nature of mechanical and electrical disturbances, especially where events tend to fade and are not always linked to clear operational consequences.
- Dedicated torsional vibration measurement capability is a key differentiator in risk management. Units with direct torsional measurement can detect sustained or weakly damped oscillations that may not be visible in standard vibration monitoring, enabling early detection, improved event attribution, and more evidence-based operational decisions. Conversely, units without such dedicated measurement rely on indirect indicators and may need to apply more conservative operational rules or depend more on external studies and coordination with TSOs and OEMs.
- Systematic measurement and data archiving not only support event analysis but also provide a baseline for future comparison. Documenting the current situation enables early detection of gradual changes or emerging risks and supports long-term trend analysis and proactive asset management (ENTSO-E, 2026).
- In line with the project's objectives and stakeholder input, particular attention should be given to disturbances that do not result in trips or immediate alarms. These moderate but repeated events may accumulate

mechanical fatigue and pose a risk of sudden failure, even though they are less visible in routine monitoring. Effective risk management requires that monitoring and analysis routines are designed to capture and evaluate such 'non-obvious' risks, ensuring that operational decisions are based on a comprehensive evidence base.

To ground these points in reality, the next section presents several field examples and practical observations.

4.3 CASE STUDIES AND PRACTICAL EXAMPLES

Based on stakeholder interviews and reference group discussions, several anonymised field examples were collected from Nordic NPPs. These include:

- Interviewees described plastic deformation in couplings observed after certain events (for example, an out-of-phase synchronization at one plant), indicating mechanical strain relevant for maintenance and risk assessment.
- Some interviewees reported lateral vibrations after grid disturbances, sometimes accompanied by an audible thump in the plant.
- Some interviewees reported occasional SSR protection trips that are difficult to interpret. Furthermore, not all units have direct torsional measurements to help analyse these incidents.
- Several interviewees highlighted the challenge of linking inspection findings to specific events, especially when mechanical issues (e.g. minor coupling damage found during maintenance) are discovered long after the triggering grid disturbance.

The reference group considered a recent example of low-frequency active-power oscillations observed in grid-side measurements (≈1.4 Hz, ±10 MW variation), technically relevant. However, routine measurement and archiving of suitable electrical waveforms is limited, making it difficult to confirm how often similar oscillations occur in normal operation. Improved correlation of electrical and mechanical measurements is seen as a key enabler for credible learning.

Overall, the evidence base is qualitative and experience-driven, reflecting practical challenges in measurement, attribution, and systematic learning across plants. These field observations highlight the need for proactive measures, which are outlined in the next section on recommendations.

4.4 RECOMMENDATIONS FOR MITIGATION AND MONITORING

To proactively manage mechanical risks, NPP operators should consider the following measures:

- Protection for sub-synchronous stress: Consider a layered approach combining (i) electrical SSR protection (typically implemented in the plant's protection system) and (ii) mechanical torsional-stress protection or equivalent mechanical safeguarding (if available). Both the investment decision and the operational handling of alarms/trips (including start/stop logic and operator procedures) sit primarily with the NPP owner/operator, informed by the assessed present and future SSO/SSR risk.

- Coordinated monitoring and recording: Strengthen mechanical monitoring on the unit side (vibration monitoring with torsional measurement where feasible) and ensure that the electrical event recordings needed to characterise the initiating grid disturbance are also available. The mechanical measurement system is normally an NPP responsibility (installation, triggering, analysis workflow). For the electrical measurements, responsibilities should be agreed between the NPP and the TSO: plant-side recordings (generator terminals, plant PMU data and relay/fault-recorder waveform recordings) are typically owned by the NPP, while recordings in the 400 kV switchyard and wide-area PMU data may more naturally be handled by the TSO. To get improvements started, it should be explicit who owns each measurement chain, how data is time-synchronised, and how it is shared after events.

- Joint post-event analysis: Systematize post-event reviews as a collaborative process between the mechanical and electrical domains (typically the NPP, covering mechanical response and plant recordings, together with the party providing the relevant electrical measurements, TSO and/or NPP depending on measurement location). Use aligned timelines (time synchronisation), share agreed data packages, and establish clear triggers and turnaround times for analysis. In practice, this point becomes straightforward once the monitoring and recording responsibilities in the previous item and the analysing part are defined and implemented.

- Responsibility split (typical): The NPP owns unit-side protection, mechanical monitoring, and plant-side recordings; the TSO owns switchyard and wide-area measurements; post-event analysis and follow-up actions are best handled jointly, with OEM support when settings, limits, or model validation are involved.

- Collaborate actively with TSOs and original equipment manufacturers (OEMs) for data exchange, joint event reviews, and updated protection settings. *Note:* In this context, OEMs are the turbine, generator, excitation/control, and protection-system suppliers that typically hold or validate unit-specific shaft data (e.g., torsional mode shapes, damping assumptions, stress limits) and provide guidance or approval for changes to protection and control settings.

- Validate shaft models and protection routines after major upgrades or changes in operating conditions.

- Continue to apply conservative settings and margins where direct torsional monitoring is lacking.

In summary, combining robust protection, improved monitoring, systematic analysis, and active collaboration enables NPPs to manage mechanical risks more effectively. Management support is essential to ensure that sufficient resources and attention are devoted to these measures.

4.5 GAPS AND OPPORTUNITIES FOR IMPROVEMENT

Even after implementing the above measures, there remain broader gaps and opportunities for improvement. This section highlights those gaps from two perspectives: first by learning from a recent major European grid incident, and then by addressing specific plant-level challenges identified by stakeholders.

External learning from recent European incidents (ENTSO-E perspective)

The ENTSO-E final investigation of the Iberian blackout on 28 April 2025 highlights that the ability to reconstruct events and derive credible learning can be constrained by data availability, data quality, and governance as by technical complexity (ENTSO-E, 2026). While the Iberian incident context differs from the Nordic NPP mechanical risk context addressed in this report, the categories of gaps identified by ENTSO-E are directly relevant here. They limit the ability to correlate grid disturbances with plant-side mechanical response and to justify protection settings, operating procedures, and mitigation measures using a transparent and reproducible evidence base.

Key data- and process-related gaps identified in the ENTSO-E investigation include:

- **Incomplete disturbance recordings (oscillography):** Missing or unavailable relay oscillography and disturbance recordings, including from protections that operated, can prevent verification of disconnection causes, precise timing, and compliance with assumed withstand capabilities.
- **Limited wide-area measurement visibility and exchange:** Insufficient PMU coverage and, in particular, limited ability to exchange PMU data efficiently between TSOs reduce the ability to localise oscillations, reconstruct disturbance propagation, and align timelines across control areas.
- **Cross-party data governance and timeliness:** Event investigations may be delayed or forced to rely on simplifying assumptions when data requests, formats, access rules, and delivery timelines are not predefined and routinely exercised across TSOs, DSOs, and system users.
- **Limited visibility of embedded or non-observable DER behaviour:** Disconnection and reconnection behaviour of small embedded generators (e.g. distribution-connected PV below typical observability thresholds) can materially influence disturbance trajectories yet may be poorly measured and difficult to quantify ex post.
- **Protection-setting traceability (including measurement location):** Where voltage is not measured at the point of connection, or where settings, time delays, and hysteresis are not consistently documented together with supporting records, it becomes difficult to validate that protection behaviour matches withstand expectations.

- **Lack of consistent post-event snapshots and model inputs:** Without a standardised post-event data package (including time-synchronised network state, key set-points, topology, and unit statuses), simulation-based reconstruction and subsequent learning become less repeatable and more uncertain.
- **Readiness not routinely tested:** The ability of all relevant parties to provide required datasets quickly and with appropriate quality benefits from routine readiness checks. Without such checks, investigations risk being limited by practical data-handling constraints rather than by technical understanding.

Together, these observations underline that effective post-event learning depends on an end-to-end evidence chain that spans measurement, recording, data access, and governance across organisational boundaries.

Project-level gaps identified by stakeholders

While the ENTSO-E investigation provides a system-level reference, the interviews and reference-group discussions in this project indicate that similar challenges manifest at plant level in a different, but closely related, form.

Gap: Evidence generation and ownership in normal operation.

Beyond the availability of protection records and event-triggered disturbance recordings, stakeholders highlighted a practical gap in systematic measurements during normal operation. The absence of continuous or routinely archived high-resolution electrical measurements limits the ability to quantify how often low-frequency power swings or sub-synchronous phenomena occur, to distinguish persistent behaviour from rare edge cases, and to evaluate whether repeated 'non-tripping' events may contribute to long-term mechanical duty or fatigue accumulation. While dedicated systems such as SSR protection provide effective safeguarding against acute high-consequence events, they are today used primarily as protection rather than as measurement and analysis tools, limiting their potential to continuously track sub-synchronous exposure and to identify recurring or long-duration phenomena that do not necessarily trigger alarms or trips. Several stakeholders explicitly pointed to limited access to wide-area measurements, including PMU data held by the TSO, as a practical constraint for event correlation and joint learning. As a result, conclusions about exposure are often drawn from isolated events, protection operations, or indirect indicators rather than from a consistent statistical or trend basis. A closely related consequence is the difficulty of linking mechanical findings identified during revision or overhaul to specific grid events, since such checks are often performed long after the disturbance and without sufficiently correlated electrical time-series data.

Barrier: Governance and business case.

The reference group emphasised that the principal limiting factor is often not the existence of suitable measurement technology, but governance. Ownership of measurement equipment, data access, analysis responsibility, and long-term operation and maintenance is frequently unclear and spread across organisational boundaries. In addition, long-term deployment of enhanced monitoring capabilities (including installation, maintenance, data handling, cybersecurity, and analysis) typically requires a clear business case in addition to technical motivation. Stakeholders noted that while there is broad technical agreement on the value of improved observability, decision-making is constrained by uncertainty regarding who benefits, who pays, and who is responsible for acting on the results. A joint, multi-year collaboration between plant owners and the TSO, potentially supported by coordinated research or framework initiatives, was suggested as a realistic model for establishing and maintaining robust measurement and analysis capability over time.

Stakeholders noted that learning from fault-ride-through (FRT) tests is not always captured systematically—especially when tests fail or produce borderline results. Establishing a standard test log, an agreed data package (electrical waveforms and relevant plant indications), and a short joint review with the TSO and relevant suppliers would increase the value of FRT tests as structured inputs to procedures, settings validation, and coordination.

5 Conclusions and Recommendations

5.1 SYNTHESIS OF FINDINGS FROM ALL THREE STEPS

Based on (i) the literature review, (ii) the stakeholder interviews, and (iii) the analysis of risk factors and existing solutions, the three steps of this study point to a consistent picture from the generator shaft's perspective. The technical background confirms that grid disturbances are experienced as mechanical stress in the turbine–generator shaft system (EPRI, 2006; Siemens PTI, 2018). Sudden faults, switching events, and sub-synchronous currents all introduce oscillatory torque that propagates along the shaft line (EPRI, 2006; IEEE, 1985). Established guidance has long recognised that converter controls and inverter-based resources can contribute to sub-synchronous oscillations under certain conditions (CIGRE, 2014), and more recent surveys and updated guidance further document such events in converter-dominated systems (IEEE PES IBR SSO Task Force, 2022; CIGRE, 2023). At the same time, it shows that preventive measures, such as dedicated protection relays, conservative grid design, and added damping, have so far prevented shaft damage in the Nordic nuclear fleet (Energiforsk, 2016:295; Energiforsk, 2017:355). In practice, severe historical failure modes, such as those seen at Mohave, have been avoided through cautious engineering despite ongoing grid changes (Anderson et al., 1999; EPRI, 2006).

- **Defined relevant grid-event families (Steps 1–2):** This report defines three event families with mechanical relevance for Nordic NPP shafts: (i) faults/switching/high-speed reclosing (transient torsional interaction), (ii) classical SSR linked to series compensation, and (iii) device-dependent SSO (umbrella term) including SSTI and converter/IBR-driven interactions (Section 2.4).
- **Analysed monitoring and protection solution types (Steps 2–3):** Existing solutions are analysed by function rather than by vendor catalogue: unit-side SSR/torsional relays, mechanical vibration/torsional monitoring, disturbance recording (relay/DFR waveforms and PMU data), time synchronisation, and post-event analysis workflows (Sections 2.5.2–2.5.3, 4.2, 4.4).
- **Analysed risk factors linked to the defined events (Step 3):** For each event family, risk is driven by proximity and severity (e.g., close-in faults), operating point and damping, and system conditions such as inertia, short-circuit strength, topology, series-compensation exposure, and converter-dominated interactions (Sections 4.1 and 2.6).

The stakeholder interviews add an operational perspective to these findings. Several interviewees described that major grid events, such as nearby faults, result in clear mechanical responses, including increased vibration levels or torsional stress, which are closely monitored. Interviewees also emphasised that less obvious, repeated disturbances that do not trigger protection may still contribute to fatigue accumulation over time, consistent with literature emphasis on cumulative duty from non-trip events (EPRI, 2006; Energiforsk, 2016:295). The interviews further indicate differences between plants in how clearly such effects can be observed. Facilities with more advanced monitoring systems gain direct insight into shaft behaviour, while others rely on indirect indicators and more conservative operating assumptions. This reinforces the need for improved and more systematic monitoring of torsional response (Energiforsk, 2016:295; ENTSO-E, 2026).

The risk-factor analysis in Chapter 0 integrates these observations. It shows that the mechanical impact of a grid event depends strongly on location, operating point, and system conditions. Faults close to the plant, occurring under weak-grid conditions and high load, result in the highest torsional stress. If such events coincide with lightly damped torsional modes, transient responses may develop into sustained oscillations. Stronger grids and reduced loading generally limit the mechanical impact. Existing protection and damping measures are effective in many cases, but the analysis also identifies gaps where mechanical stress may remain below protection thresholds yet still contribute to long-term fatigue, or where new grid operating patterns challenge existing assumptions.

Taken together, the literature review, stakeholder input, and analytical work show that the grid-induced mechanical duty experienced by NPP turbine–generator shafts is evolving. While the underlying physics remain unchanged, changes in the Nordic power system have led to new disturbance patterns and operating conditions (Energiforsk, 2021:835; Energiforsk, 2025:1091). This reinforces the need for robust monitoring, analysis, and coordination between plant operators and grid stakeholders, particularly regarding evidence quality and data exchange after events (ENTSO-E, 2026). Sections 5.2–5.3 of this report build on this synthesis: Section 5.2 presents practical recommendations for NPP stakeholders, while Section 5.3 outlines areas where further research or implementation efforts are needed to ensure continued mechanical integrity as the power system develops.

5.2 PRACTICAL RECOMMENDATIONS FOR STAKEHOLDERS

This section translates the findings from the literature review, stakeholder interviews, and risk analysis into practical actions. The recommendations are primarily directed at nuclear power plant owners and operators, with emphasis on measures that can be implemented within existing organisations and in coordination with transmission system operators. The aim is to strengthen mechanical integrity by improving detection, understanding, and management of grid-induced stress. Several recommendations reflect themes raised in the interviews, while others follow from the technical background and risk analysis.

1. Maintain dedicated SSR or torsional stress protection (layered where relevant): Ensure that each unit has dedicated protection capable of detecting sub-synchronous phenomena. Where applicable, distinguish between (i) electrical SSR protection in the plant protection system and (ii) mechanical torsional-stress protection or equivalent mechanical safeguarding. The decision to implement alarm-only vs trip functionality, and the operational handling of alarms/trips, is primarily for the NPP to decide based on assessed current and future risk; it should be supported by clear operating procedures and periodic testing/calibration.

2. Upgrade monitoring and event recording with clear ownership: Strengthen unit-side mechanical monitoring (vibration monitoring including torsional measurement where feasible) and ensure that electrical event recordings needed to characterise grid disturbances are captured as well. The mechanical measurement system is typically an NPP responsibility (installation, triggers, analysis workflow). Plant-side electrical recordings (generator terminals, protection oscillography, plant PMU data and relay/fault-recorder waveform recordings) are also typically owned by the NPP, while recordings in the 400 kV switchyard and wide-area PMU data may be owned by the TSO. To make the capability effective, agree and document who owns each part, how systems are time-synchronised, how long data is retained, and how it is exchanged after events.

3. Establish routine, joint post-event analysis: Implement a clear procedure to review significant grid events and correlate electrical disturbance signatures with mechanical response. This should be performed as a collaboration between the NPP (mechanical response, plant recordings, inspection findings) and the party providing the relevant electrical measurements (TSO and/or NPP). Define triggers (e.g., close-in faults, high-speed reclosing, oscillation indications, repeated non-tripping events), define an agreed data package and timeline, and document lessons learned and follow-up actions. In practice, this becomes considerably easier once the monitoring/recording responsibilities and data exchange in the previous item and the analysing part are in place.

4. Interviewees emphasised stronger TSO and original equipment manufacturer (OEM) coordination: Proactively coordinate with the transmission operator and equipment suppliers to improve shared understanding and response to these risks. This includes exchanging data, for example arrange to receive relevant grid disturbance records or PMU data from the TSO after major events, and provide the plant's vibration or relay data in return. Hold joint review meetings (with TSO protection engineers and OEM experts) for significant incidents to ensure protection settings and models remain appropriate. Such collaboration helps align grid-side and plant-side measures and can reveal whether adjustments (like tuning an HVDC controller or updating a relay set-point) are needed to reduce mechanical stress on the unit.

5. Revalidate models and settings after changes: Treat major system or plant changes as triggers for fresh analysis. If new grid developments occur (e.g. a nearby HVDC installation, changes in network configuration, higher levels of inverter-based resources (IBR)) or plant modifications are made (such as turbine upgrades or control system updates), revisit the turbine-generator's torsional risk assessment. Use updated studies, from simplified frequency scans to detailed EMT simulations, to check whether existing protection schemes, damping measures, and operating limits are still sufficient. Adjust protection setpoints or operational guidelines as needed to account for the new conditions.

6. Apply conservative margins when uncertainty exists: Where the mechanical response is not fully measurable or understood, apply a conservative approach. This could mean using tighter operating limits (for example, avoiding continuous full-power operation under certain weak-grid conditions), maintaining extra margins in protection settings, or increasing inspection frequency for components like couplings. This approach is also consistent with stakeholder descriptions of how risks are managed when observability is limited. Over time, as monitoring improves and knowledge grows, such margins can be refined.

Each of these recommendations is practical and immediately actionable for NPP operators. They focus on enhancing the plant's ability to detect, withstand, and learn from grid-induced mechanical stresses. By implementing these measures, and securing management support to do so, plant owners can better protect their generator shafts and proactively manage mechanical integrity in an evolving grid environment.

5.3 SUGGESTIONS FOR FURTHER RESEARCH OR IMPLEMENTATION

While the recommendations above address immediate actions, there are strategic areas where additional research and coordinated implementation would help the industry stay ahead of emerging challenges. The following suggestions outline next steps to deepen understanding and enhance long-term risk management:

1. Advanced torsional monitoring and digital twin development: Pursue a pilot project to deploy next-generation torsional monitoring at one or more plants, potentially integrating a digital twin model of the turbine–generator shaft. By collaborating with research partners or OEMs, operators can simulate and predict shaft behaviour under a wider range of scenarios (including complex grid disturbances) and validate model predictions against high-fidelity field measurements. This effort would improve real-time awareness of shaft stress and provide more powerful tools to anticipate how novel grid events might affect mechanical integrity.

2. Study cumulative fatigue from repeated disturbances: Initiate a focused research study on how moderate, non-trip events contribute to long-term fatigue in turbine and generator components. This could involve material testing, refined fatigue modelling, and analysis of historical disturbance data across multiple units. The goal is to quantify how much "life" is consumed by frequently occurring vibrations and to update maintenance guidelines accordingly. Results from such research would help operators decide if inspection intervals or component replacement criteria should be adjusted in light of the evolving disturbance environment.

3. Enhance NPP–TSO data sharing and joint analysis: Establish a formal program or working group for cross-company disturbance analysis. Building on the collaboration recommended in Section 5.2, this initiative would create a structured process for NPPs and the TSO to pool observations from significant grid events. For example, it could include a shared database of disturbance records and shaft responses, and regular

technical workshops to review findings. Joint analysis would improve the quality of individual plant risk assessments and feed into broader grid planning. This approach ensures that lessons learned (such as the impact of a new HVDC link or protection scheme on nearby plants) are captured and acted upon across the system.

4. Refine simulation models for future grid scenarios: Support further development of integrated grid–plant simulation studies that reflect the Nordic system's trajectory (increased inverter-based generation, new control systems, etc.). This may involve funding additional EMT simulations or dynamic studies that include detailed turbine–generator shaft models for nuclear units under prospective grid conditions (for example, 2030 or 2040 scenarios). The outcome would be improved forecasting of risk areas. For example, such studies could clarify if a planned network change might introduce an SSTI issue. This would enable proactive adaptation of protection settings or operating procedures before those changes materialize.

5. Update industry guidelines and training: Work through industry bodies (such as Energiforsk, VGB PowerTech, or CIGRE) to incorporate recent findings into standards and training programs. This could include updating guidelines on SSR and SSTI studies to account for power-electronic interactions, developing training modules for control room staff on recognizing and reacting to abnormal vibration indications, and drafting best-practice documents on coordinating torsional protection between plants and TSOs. Driving these updates will help the broader industry keep pace with the changing risk landscape. New projects or retrofits would benefit from the latest knowledge. For instance, advanced monitoring could be included in design criteria, and sub-synchronous interaction studies (SSR/SSTI/SSO) should be considered as part of the connection and integration studies for new HVDC projects located close to large synchronous generators (e.g. existing Nordic HVDC interconnectors).

Each of these suggested efforts builds on the findings of this study and the actions in Section 5.2, looking beyond the immediate horizon. Investing in research and collaborative development now will pay off in greater resilience later. It will equip plant operators with better predictive tools, reduce uncertainty in decision-making, and strengthen partnerships with the grid operator and the research community. Ultimately, these steps will help ensure that as the Nordic power system continues to transform, the nuclear fleet can rely not only on robust current measures but also on improved knowledge and technology to safeguard mechanical integrity.

5.4 JUSTIFICATION FOR INVESTMENT IN MONITORING AND PROTECTION

Proactive investment in monitoring and protection is essential for safeguarding plant reliability and avoiding costly surprises as the Nordic power system evolves.

As demonstrated throughout this report, the Nordic power system is undergoing rapid transformation, with increased integration of HVDC links, inverter-based resources, and more variable system inertia. These changes introduce new disturbance patterns and risk combinations that were less prominent in earlier decades.

Furthermore, systematic measurement and data archiving provide a valuable historical baseline. By documenting the current situation, NPPs enable future comparison, support trend analysis, and allow early detection of gradual changes or emerging risks. To make such a baseline useful in practice, relevant TSO-held PMU data should be made available with the NPPs after significant events and, where feasible, through agreed routines for broader analysis. Without access to time-synchronised wide-area measurements, the plants' ability to reconstruct disturbance sequences, correlate electrical events with mechanical response, and learn from repeated non-tripping events remains unnecessarily limited.

Section 2.5.3 shows that international standards and recent events consistently recommend proactive monitoring and protection even for plants with no historical incidents. Stakeholder interviews and field experience (Sections 3.2 and 3.4) indicate that moderate but repeated events may accumulate mechanical fatigue, and that observability varies across plants. In particular, interviewees described that risks can remain hidden when measurement capability is limited, until they result in outages or damage.

Section 4.2 highlights that limited measurement capability can delay corrective actions. Interviewees described that units with direct torsional measurement and systematic routines are more confident in their decisions, while others rely on conservative margins and external studies.

Investing in improved monitoring and protection is cost-effective, aligns with best practice, and helps prevent expensive repairs, outages, and reputational risk. The cost is small compared to the impact of a major shaft failure or forced shutdown.

A second, practical reason for establishing such a baseline is that it enables future change to be demonstrated. If disturbances are expected to evolve over time, current conditions must be documented with sufficient quality (what is measured, where, how often, and with what bandwidth) to allow meaningful comparison and attribution in future reviews.

Moreover, increasing safety margins by reducing production (derating) can be highly costly. Improved monitoring and analysis can reduce uncertainty and, over time, help justify proportionate measures—so that operational restrictions are applied where needed, but avoided where evidence shows they are not.

Continuous improvement and proactive risk management are hallmarks of safe, reliable operation. Even without past incidents, evolving grid conditions and cumulative risks make investment both prudent and necessary for Nordic NPPs.

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Appendix

INTERVIEW QUESTIONNAIRE VIBRATIONS AND GRID EVENTS

Purpose and framing (to be read to interviewees)

The purpose of this interview is to collect practical experience and expert judgement regarding how already known grid phenomena manifest as mechanical stress, torsional vibration, or fatigue in turbine–generator systems, and how such risks are currently detected, assessed, and managed inside the power plant.

The interview does not aim to further investigate or characterise the electrical grid phenomena themselves. Those aspects are addressed within other Energiforsk programmes. Instead, the focus here is strictly on mechanical consequences, protection of the turbine–generator shaft line, and plant-internal experience.

The discussion is qualitative and experience-based. No confidential operational details are required.

Please describe and elaborate in your response.

A) Background and Role
Purpose: Establish context for interpreting experience related to turbine-generator systems.

1) Please briefly describe your role and area of responsibility related to turbine, generator, shaft system, or mechanical protection.

2) How long have you worked with turbine–generator systems or vibration-related topics?

B) Experience of mechanical effects from grid events
Purpose: Identify which known grid phenomena are mechanically relevant from a plant perspective.

1) From your experience, have electrical grid disturbances led to mechanical effects in turbines or generators (e.g. torsional vibration, shaft stress, fatigue, abnormal wear)?

    - If yes, please describe the mechanical manifestation, not the electrical origin.
    - If no, please briefly explain why.

2) Among the grid phenomena you are already familiar with (e.g. faults, reclosing, SSR/SSO-type events, frequency deviations), which do you consider most critical from a mechanical stress or vibration perspective, and why?

3) Have you seen trends over time (frequency, severity, or character of events) that differ from historical experience?
Please elaborate.

C) Operating conditions and sensitivity
Purpose: Understand under which internal conditions mechanical vulnerability increases.

1) Are there specific operating conditions under which the turbine–generator system is particularly sensitive to grid-induced mechanical stress (e.g. high load, certain shaft configurations, maintenance states, weak-grid operation)?

2) Have you observed that similar grid events lead to different mechanical responses depending on unit condition or operating mode?

D) Torsional vibration and shaft dynamics
Purpose: Assess how shaft-dynamic behaviour is understood and used in practice.

1) How relevant are torsional vibration and shaft-dynamic phenomena for your units today?

2) What shaft-dynamic information is available for your units (e.g. natural frequencies, mode shapes, damping)?

   - How was this information obtained (OEM data, studies, measurements)?
   - How confident are you that it reflects current operating conditions?

3) Have torsional vibration phenomena been linked in practice to:

   - inspection findings or fatigue concerns,
   - alarms or protection operation, or
   - operational restrictions?

4) Which parts of the turbine–generator shaft line do you consider most mechanically critical, based on experience?

E) Sub-synchronous phenomena – mechanical perspective
Purpose: Focus on mechanical exposure, not electrical mechanisms.

1) Has exposure to sub-synchronous phenomena (e.g. SSR, SSTI, SSO) been assessed from a mechanical risk perspective for your units?

2) If such phenomena have been observed or analysed, how have they manifested mechanically (stress, vibration, damping concerns)?

F) Monitoring, protection, and internal data
Purpose: Understand observability of mechanical risk.

1) What monitoring or protection related to torsional vibration or shaft stress is currently in place?

2) How are grid disturbances and potential mechanical responses handled in post-event analysis within the plant?

3) From your perspective, what mechanical-side data or measurements are most valuable for assessing grid-induced stress on the turbine–generator system?

G) Mitigation and operational practice
Purpose: Identify practical risk-reduction measures inside the plant.

1) What measures are used to manage grid-induced mechanical risk (e.g. protection settings, operational constraints, monitoring practices)?

2) From experience, which measures are most effective, and where do you see limitations or trade-offs?

H) Forward-looking mechanical risk
Purpose: Capture expert judgement on future exposure, strictly from a mechanical standpoint.

1) Looking ahead 5–10 years, do you expect the mechanical exposure of turbine–generator systems to grid-induced stress to change?

2) Where do you see the largest uncertainties or knowledge gaps related to protecting turbine-generator systems from such stress?

GRID-INDUCED MECHANICAL STRESS ON THE TURBINE-GENERATOR SHAFT

Seen from the turbine–generator shaft of a Nordic nuclear power plant, the changing power system is experienced as short, sometimes repeated torque disturbances. This report explains which grid events are most relevant for mechanical integrity, from faults and switching to classic sub-synchronous resonance and newer converter-driven interactions involving HVDC and inverter-based resources (IBR, including inverter-interfaced generation and loads). A key finding is that many risks remain difficult to confirm or rule out without adequate measurements. The report therefore focuses on practical actions that make risk visible and manageable: dedicated torsional or SSR protection, improved vibration monitoring and event recording, and routine post-event analysis linked to TSO data. These measures support faster investigations, better targeted maintenance, and more robust decisions as the Nordic grid continues to evolve.

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