

Power System Frequency Measurements and Requirements: Assessing the Needs in the Nordic Power System

Evaluating Frequency Constraints and Refining Normal Frequency Range for the Future Nordic Power System

Master's thesis in Sustainable Electric Power Engineering and Electromobility

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Cover: PSSE Nordic Power System Model 2040

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Abstract

The Nordic power system is undergoing a major transition, with large-scale renewable energy development expected over the next decades. The increasing share of inverter-based generation, higher production variability, and reduced system inertia will affect the frequency stability of the future Nordic grid. The aim of this thesis is to study frequency measurement methods, frequency sensitive components, and expected frequency variability under normal operating conditions of the future Nordic power system.

Higher renewable penetration, with inverter-based connections introduces new challenges such as increased resonance and frequency variability, which increases the need of novel frequency measurement approaches. This study discusses these needs and commercial products such as relays, PMUs and controllers, that use different frequency measurement methods. The review of existing frequency measurement methods highlights various drawbacks of accuracy, signal quality and hardware implementation. Sensitive power system components for frequency such as generators, turbines, transformers, load side equipment, have also been discussed with a focus on the normal operational limits.

A frequency variability study was conducted for the future Nordic power system based on the PSSE Nordic 44 model. The original Nordic 44 model was updated to reflect the current Nordic system and two simulation cases were developed considering operational snapshots for a winter day and a summer day. The frequency dynamic behavior was validated using actual frequency measurements. Then, two future scenarios for summer and winter were developed and the future system frequency variability was analysed by applying time series load changes.

The results show that the frequency deviation from 50Hz increases with a greater variation in load. Increasing deviation rates are especially observed below 50Hz. Also, the summer day scenario showed a higher frequency fluctuation beyond the normal operational frequency limits compared to the winter day scenario. Future scenarios also showed higher frequency ramping compared to the present system model due to reduced overall system inertia.

The findings indicate that the future Nordic power system will experience greater normal frequency variability with greater deviations and frequency ramps. Understanding system changes, being aware of sensitive components, adapting operational standards, and implementing novel frequency measurements to accommodate these changes will be crucial to maintaining system stability.

Keywords: Nordic power system, Inverter-based generation, Frequency variability, PSSE Nordic 44 model, System inertia, Normal operational frequency.

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List of Acronyms

List of acronyms that have been used throughout this thesis in alphabetical order:

aFRR	Automatic Frequency Restoration Reserve
AGC	Automatic Generation Control
CPA	Complex Prony Analysis
DFT	Discrete Fourier Transform
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FCR-D	Frequency Containment Reserve – Disturbance
FCR-N	Frequency Containment Reserve – Normal
FFR	Fast Frequency Reserve
FFT	Fast Fourier Transformation
FRR	Frequency Restoration Reserve
HVDC	High Voltage Direct Current
IGD	Implementation Guidance Document
IEC	International Electrotechnical Commission
LF	Loop Filter
LFSM-O	Limited Frequency Sensitive Mode – Overfrequency
LFSM-U	Frequency Sensitive Mode – Underfrequency
LSE	Least Square Error
mFRR	Manual Frequency Restoration Reserve
NTNU	Norwegian University of Science and Technology
OFGS	Over Frequency Generation Shedding
PD	Phase Detector
PFR	Primary Frequency Response
PLL	Phase Locked Loop
PMU	Phasor Measurement Unit
RMS	Root Mean Squared
RoCoF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SSR	Sub Synchronous Resonance
TSO	Transmission System Operator
UFLS	Under Frequency Load Shedding
VCO	Voltage Controlled Oscillator
WAMS	Wide Area Monitoring Systems
WMU	Waveform Measurement Unit

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Parameters

P_m	Mechanical power
P_e	Electrical power
J	Total moment of inertia
ω_r	Rated angular speed
ω_m	Mean angular speed
H	System inertia
S	Rated power
E_{kia}	Kinetic energy



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1

Introduction

This chapter outlines the background of the thesis project, defines the scope of the study, states the project objectives and the study methodology. In addition, the final section describes the structure of the report.

1.1 Background

In an electric power system, the balance between electricity consumption and generation must be maintained to ensure grid frequency stability. Electric power systems are typically operated at a nominal frequency of 50 Hz (or 60 Hz) according to the country or regional requirement.

The Nordic power system is a synchronized power network of Sweden, Finland, Norway and the eastern part of Denmark. As per the International Energy Agency electricity generation mix data 2023 [1], major part of the electricity generation of the Nordic power system comes from hydro, nuclear and wind. The Nordic power system is divided into bidding areas, including four in Sweden (SE1, SE2, SE3, SE4), five in Norway (NO1, NO2, NO3, NO4, NO5), one in Finland (FI), and two in Denmark, with only the eastern part of Denmark (DK2) belonging to the Nordic system. This is presented in Figure 1.1.



Figure 1.1: Bidding Areas of the Nordic Power System [2]

1. Introduction

The Nordic TSOs (Energinet, Fingrid, Statnett and Svenska kraftnät) are responsible for nordic power system balance through maintaining the power system frequency close to its nominal value of 50 Hz. In the Nordic system, the frequency tolerance for normal operation is set at 49.9–50.1 Hz [3].

The Nordic power system frequency quality has reduced over the last years indicated by increased minutes outside normal frequency band [4]. The TSOs target is to keep the cumulative minutes outside the normal frequency range for around 10,000 minutes per year [5]. As shown in Figure 1.2, before the year 2020 the number of minutes outside the normal frequency band is higher than the targeted value, showing increased fluctuation of frequency under normal operation. The last four years show slight improvement, which may be the result of implementing new market mechanisms and increasing the volumes for the automatic frequency restoration reserve [6].

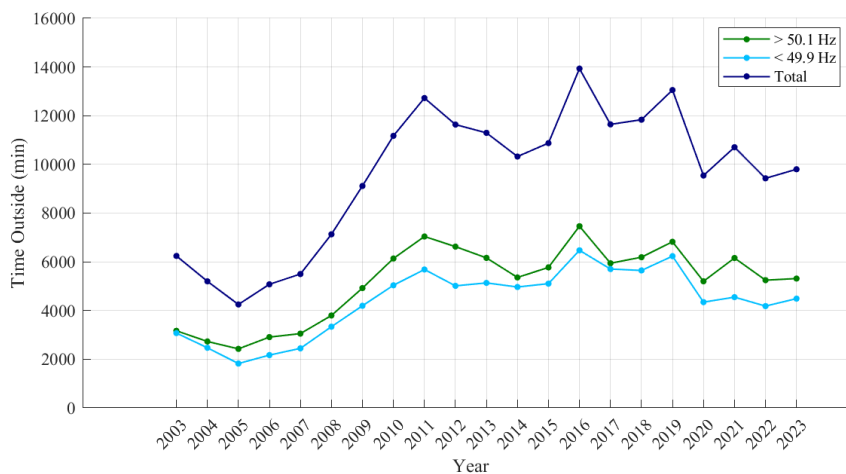


Figure 1.2: Total minutes outside the standard frequency range [6]

In addition, total minutes outside the frequency above the 50.2 Hz and below the 49.8 Hz were analyzed. As shown in the Figure 1.3, last few years show an increment in minutes by representing the higher frequency change from the nominal value.

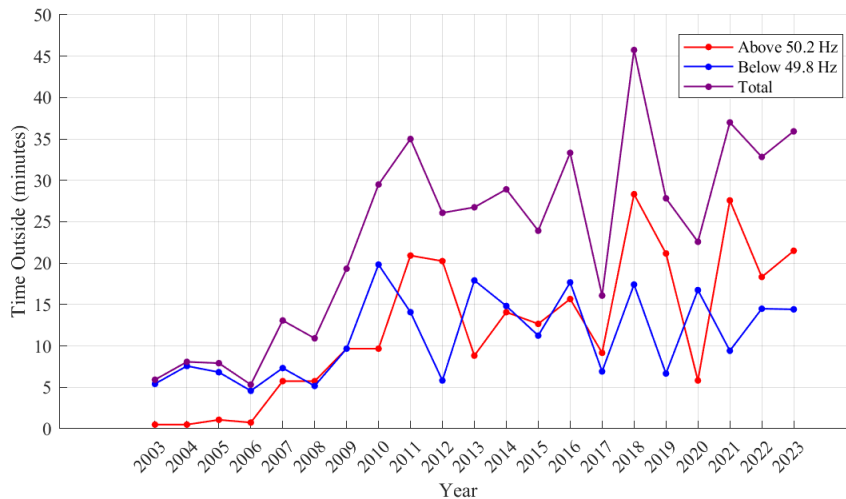


Figure 1.3: Total minutes of frequency > 50.2 Hz and < 49.8 Hz [6]

The most likely reasons for the impact on frequency quality of the Nordic power system is the integration of large-scale renewable power into the system, the increase of electronic power interfaces, the reduction of inertia in the system, and the design of the electricity market [7]. Historically, power production was dominated by synchronous machines connected to the grids, which supported the system with rotational inertia. This made the large-scale grids capable to withstand the system deviations. The higher share of inverter based power production in present and future power systems will result in a decrease in the system inertia and in an increase in the fluctuation of the grid frequency [8].

With this present context of the Nordic power system, this thesis investigates the frequency fluctuation in future power system under normal operating conditions and the possibility to wider the frequency tolerance for normal operations to the enhance the operational flexibility of the power system.

1.2 Project Scope

This thesis focuses on the Nordic power system in the present and future context. Initially, the frequency as an indicator and control variable of the power system is discussed. Then, the frequency measurement techniques are explored, and components sensitive to frequency variations of the Nordic power system are identified. Nordic power system simulations are carried out through the PSSE software and the previously developed Nordic 44 network model enhanced to match with the present context. Different future operational scenarios are analyzed to assess frequency fluctuations under normal operating conditions. The study also discusses the needs, opportunities, and challenges of widening the normal frequency band for the Nordic power system.

This study focused on theoretical and simulation-based evaluations according to the scope, and excludes practical (lab-based) frequency measurement tests, economic

implications, stakeholder perspectives, and hardware validation. Ultimately, the findings are intended to inform potential updates to frequency regulations, enhancing the stability and flexibility of the Nordic power grid.

1.3 Project Objectives

The key research questions addressed in this study include:

- Will different frequency measurement methods at present affect the fulfillment of the requirements of future Nordic power system?
- What are the components of the power system that are sensitive to frequency fluctuations and their limits?
- How will the normal frequency variation change in the future Nordic power system?
- What are the needs, opportunities, and challenges of widening the normal frequency range for the Nordic power system?

The overall project aim is to discuss and examine the future frequency requirements and the normal operational behavior of the Nordic power system.

The objectives of this thesis project are;

- Discuss how frequency is derived and measured and the implications of various measurement methods in power system operation.
- Identify power system components in the Nordic power system which are sensitive to frequency fluctuations.
- Develop different operational scenarios and simulate using PSSE the future Nordic power system to identify frequency fluctuations under normal operation.
- Propose normal frequency limits with quantitative results.
- Discuss the needs, opportunities, and challenges of widening the normal frequency band for the Nordic power system.

1.4 Methodology

The methodology adopted for this study is presented in the Figure 1.4.

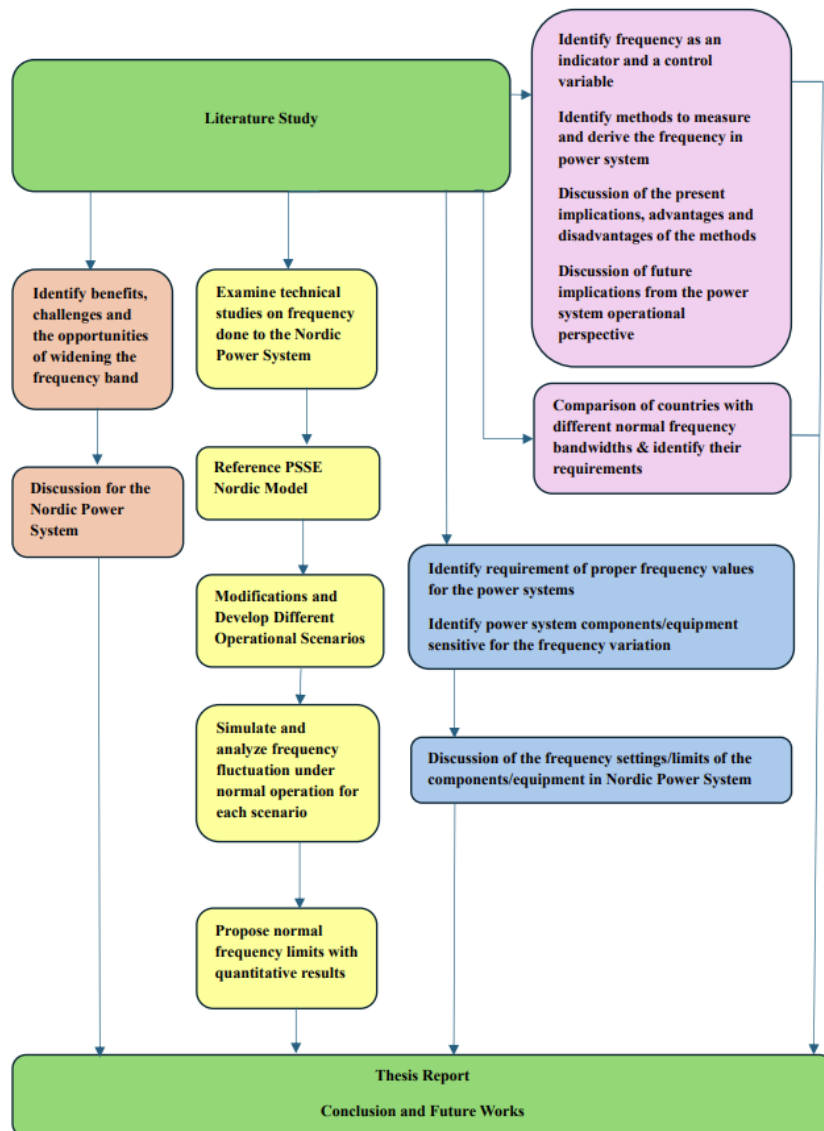


Figure 1.4: Project Methodology

1.5 Ethical and Sustainability Consideration

The study was based on data from DNV and other public sources. From ethical perspective, the study data has used accurately and transparently, without distortion or misrepresentation. Furthermore, proper citation and acknowledgment are provided for the data sources.

This thesis study aligns with the sustainability and climate strategy of DNV. That strategy comprised with the objectives to reduce the carbon footprint of their business areas. The thesis aims to provide an understanding of frequency tolerances in future Nordic power system. Therefore from the sustainability perspective, the study can support the integration of renewable energy sources for Nordic power system by enhancing the grid flexibility through greater understanding of the topic and

possibly broader frequency tolerances. This will enable low cost transition of conventional power systems to the power systems dominated by wind and solar energy, ultimately lowering carbon emissions.

1.6 Report Structure

This report comprised of eight chapters.

Chapter 1 include the introduction to the study, project scope, objectives and the study methodology.

Chapter 2 presents the theoretical background, along with discussion based on the desktop study of frequency measurement methods. The discussion focuses on the main and widely used methods in power systems. Additionally, the combined approaches and new methods utilizing waveform measurements are discussed. Finally, a comparison of frequency measurement methods is provided, highlighting their advantages, disadvantages, and applications in power systems.

In chapter 3, a comparison of normal frequency ranges of different countries and regions are summarized along with their main factors for maintaining tight or flexible normal frequency bands. The factors mainly comprised focusing on the power system technical requirements, market structure, cost and infrastructure.

A discussion on the sensitive power system components to frequency fluctuations is conducted in chapter 4 focusing on generation, transmission, distribution and end customer. Additionally, the final section presents the discussion on the related limits and criteria of Nordic power system components.

Chapter 5 describes the PSSE Nordic 44 model and updates done to develop the original model to match with the current Nordic power system. The development of future scenarios and the simulation results are described in chapter 6.

The discussion of benefits, challenges and opportunities of changes in normal frequency range is discussed in chapter 7. Chapter 8 presents the Conclusions and Future work.

2

Theoretical Background and Frequency Measurement Methods

This chapter presents the theoretical background of frequency and discusses its function as an indicator and control variable in the power system. In addition, the frequency measurement methods are elaborated focusing on the present context and future requirements.

2.1 Swing equation and Inertia

2.1.1 Swing Equation

the swing equation describes the rotational dynamics of synchronous machines connected to the grid by capturing the rotor angle variation for the power imbalances of the grid. This can be expressed as

$$P_m - P_e = J \cdot \omega_r \cdot \frac{d\omega_m}{dt} \quad (2.1)$$

where J is the total moment of inertia of the system [$kg \cdot m^2$], $P_m - P_e$ represents the power imbalance between mechanical input and electrical output [W], ω_r is the rated angular speed/mechanical angular speed [rad/s] and ω_m is the mean angular speed [rad/s] of the machines (rotor). When the electrical power output P_e increases in the system, angular speed of the machines will decrease. As a result, the mechanical power input P_m to the system needs to increase by accelerating the machines to bring the system back to the balance position. As long as the frequency remains below the nominal value, the machines must be further accelerated. Under normal system conditions, this is commonly achieved by enhancing the water flow through the turbines in hydro power plants [9].

2.1.2 Inertia

The system equivalent inertia is defined as the ratio of the kinetic energy of the rotating masses of the system to the rated power of synchronously rotating machines [10].

$$H = \frac{E_{kia}}{S} = \frac{J \cdot \omega_r^2}{2 \cdot S} \quad [s] \quad (2.2)$$

where H is the system inertia [s] and S is the rated power [MVA] of synchronously rotating machines. According to the above, more rotational mass in the system leads

to higher system inertia, providing increased kinetic energy storage of the system. This will result for the improved system performance for the frequency dynamics and system stability.

The Nordic TSOs estimate the kinetic energy of the Nordic power system (Finland, Sweden, Norway, eastern Denmark) using modelling data and real-time telemetry of individual generators [11]. The kinetic energy of the Nordic power system typically varies between 120 GWs and 280 GWs [11]. Figure 2.1 shows the annual system inertia variation from 2016 to 2024.

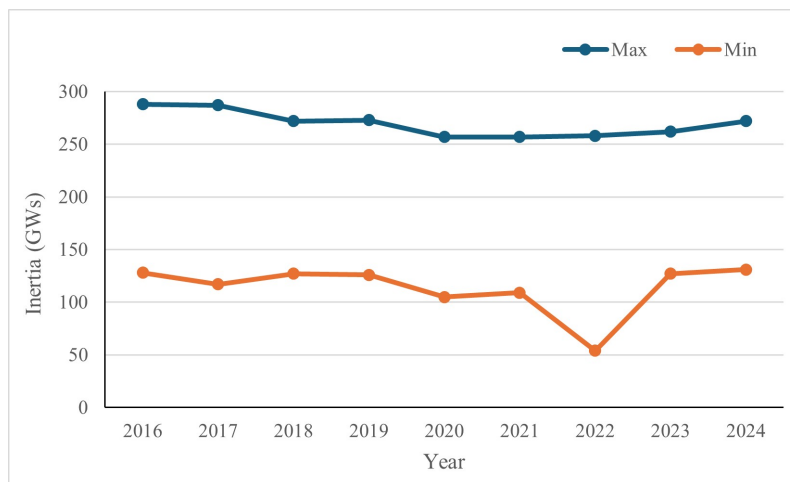


Figure 2.1: Nordic Power System Annual Inertia Variation [12]

2.2 Frequency Control Reserves

Nordic power system operates in 50Hz which is the nominal frequency of the system and the actual frequency fluctuates around this based on the imbalance between electricity production and consumption [13]. The frequency control of the Nordic power system comprised with two processes; the frequency containment process and the frequency restoration process [13]. The frequency containment reserves activate directly based on the measured frequency deviation and these are the first reserves that react for the system frequency imbalances. The frequency restoration reserves are used to bring the frequency back to 50Hz and release the activated frequency containment reserves.

The frequency control reserves in the Nordic power system comprised with three sub-groups as Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR) and the Fast Frequency Reserve (FFR) [9]. This thesis focuses on frequency fluctuations during normal system operation and therefore more emphasis is given to the FCR-N while providing a brief discussion on other frequency control reserves.

- **Frequency Containment Reserve – Normal (FCR-N)**

The FCR-N stabilize the fluctuation between electricity production and consump-

tion in normal system operation by activating automatically and proportionally in response to deviation. Accordingly, this is activated within the standard frequency range 49.9-50.1 Hz. The entity providing FCR-N must be capable of both increasing and decreasing its power production or consumption, depending on the direction of the frequency deviation. FCR-N must be able to activate approximately 63% within 60 seconds and 95% within 3 minutes [13].

The Nordic region currently ensures 600 MW FCR-N capacity throughout the year. The allocation of the required capacity among the Nordic TSOs is based on the annual consumption and generation of the previous year.

- **Frequency Containment Reserve – Disturbance (FCR-D)**

The FCR-D need to automatically activated during system disturbances. Two separate products are available for upregulation (during under frequency disturbances) and down regulation (during over frequency disturbances). The FCR-D upwards and downwards products are to be activated linearly within the frequency ranges of 49.5–49.9 Hz and 50.1–50.5 Hz, respectively [13].

- **Fast Frequency Reserve (FFR)**

The FFR provides fast power response for a short duration until the FCR-D activated during a major disturbance of the Nordic power system. This is only an upregulation product. The FFR activation threshold is at 49.5 Hz, 49.6 Hz or 49.7Hz [9]. The full activation time is 0.7–1.3 seconds depending on the activation threshold [13].

- **Frequency Restoration Reserve (FRR)**

The FRR is comprised of two categories: Automatic (aFRR) and Manual (mFRR). This is used to restore the frequency back to the nominal value of 50 Hz. The activation of an aFRR providing unit is based on a control signal sent every 10 s by the respective TSO and the maximum allowed full activation time is 5 minutes [9]. The mFRR is the only manual reserve product used in the Nordics and its full activation time is 15 minutes [13].

2.3 Role of Frequency in Power Systems

In power grids, the frequency of the system serves as both a crucial indicator of supply-demand balance and a critical control parameter for the numerous interconnected components of the power system. Below discusses the role of the frequency as an indicator and a control parameter of the components.

2.3.1 Frequency as an Indicator

Table 2.1 shows the role of the frequency of the power system as an indicator in the conditions of the power network.

Table 2.1: Role of Frequency as an Indicator

Purpose	Description
Power System Health and Stability	Power system frequency close to the nominal value (50Hz) indicates a healthy and stable system. Deviations from the nominal value signal the potential issues of the power system such as excess generation (high frequency) and excess load (low frequency).
Power System Imbalance Detection	Power system frequency indicates the imbalance of the power system. Sudden drops in frequency may represent a loss of generation, while increases suggest a drop in demand or oversupply.
Power System Fault and Event Detection	Large or rapid frequency changes in the power system indicates the system disturbances such as generator trips, system faults, or major load disconnections.
Operational Monitoring	Power system frequency used in control centers to assess the current state of the power grid. Transmission System operators continuously monitor frequency to ensure grid stability and reliability.

2.3.2 Frequency as an Control Variable

In electrical power systems, frequency also serves as a critical control variable to maintain system stability and operational reliability. This section outlines some of the key control applications of frequency in power system operations.

2.3.2.1 Primary Frequency Response (PFR)

PFR refers to the automatic adjustment of the power output by a governor or electronic controller in response to changes in the frequency of the network. In rotating machines, this control is governed by mechanical governors, which adjust control valves to respond to frequency deviations. In power electronic-based generation, frequency-based control is exerted through power electronics. The power system operates under the assumption that the primary frequency control functions autonomously and continuously, maintaining the required relationship between frequency and power without external input [14].

2.3.2.2 Automatic Generation Control (AGC)

The objective of AGC is to keep the frequency of the power system at the nominal value or the scheduled value by maintaining the balance between the generation and the load demand with the losses. AGC adjusts the generation of multiple units in the different power plants according to the load variation of the system by taking the frequency deviation Δf as the control input [15].

2.3.2.3 Under Frequency Load Shedding (UFLS)

Under frequency load shedding is designed to restore power system frequency stability after a major disturbance such as loss of power generation, loss of a bus, loss of a line or even loss of a tie-line. In these cases, the overall generation capacity will decline while system total demand remains the same by resulting frequency decrease than the nominal value. UFLS scheme designed to shed appropriate amount of load to match the available generation capacity by quickly recovering the system frequency. Therefore, frequency is considered as a control factor in UFLS to determine the amount of load to be shed based on the minimum permissible value [16].

2.3.2.4 Over Frequency Generation Shedding (OFGS)

Loss of an interconnected line causes a loss of load and leads to an excess power supply to the system. This results in over frequency. The Over Frequency Generator Shedding (OFGS) scheme is used to mitigate this issue by shedding generators when the frequency exceeds a predetermined threshold. The frequency deviation serves as a trigger signal for the governor response, causing the generator output to be reduced. If the frequency continues to increase, the OFGS relay activates and disconnects the generators from the grid. The selection of generators for shedding is based on their inertia constant, with lower inertia generators being first tripped to provide a more stable frequency response [17].

2.3.2.5 Dynamic Fast Frequency Reserve (Dynamic FFR)

Dynamic FFR operates to deliver the power response counteracting the frequency deviation in the power system. This particularly acts for the first dip or peak following a large system disturbance. This response is triggered by frequency changes, that serve as an input signal. To achieve the desired response, the frequency signal undergoes bandpass filtering with optimized time constants. Initially, a low-pass filter determines the reserve's sensitivity to rapid frequency changes, followed by a high-pass filter, which controls the duration of the response. This ensures a dynamic reserve behavior that is capable of adjusting to both frequency increases and decreases.

2.3.2.6 Grid Forming Inverters in Microgrids

Power system frequency is considered a crucial control input in the grid forming inverters, which are expected to play an increasingly key role in maintaining grid stability and integrating renewable energy sources. Unlike grid following inverters, grid forming inverters establish and regulate frequency autonomously. Various control strategies are available to manage the frequency such as droop control which adjust the inverter output power in response to frequency variation, mimicking the behavior of traditional synchronous generators [19].

2.3.2.7 HVDC Frequency Control

HVDC interconnections are used in power transfer within a synchronous AC grid or to connect two asynchronous grids within two countries or regions.

When a HVDC link interconnects two asynchronous grids, it supports frequency stability by exchanging the balancing power considering the frequency deviation. This is done through three market mechanisms; Frequency Containment Reserve, Automatic Frequency Restoration Reserve and Manual Frequency Restoration Reserve & Replacement Reserve [19][16], alternatively for larger frequency deviations through Emergency Power Control (EPC). Based on the above, frequency support from one synchronous area to the other can be provided through the HVDC link. The frequency of the receiving area will be an input for the controller in such cases and power flow on the HVDC link towards that area will vary (increase or decrease) accordingly.

The HVDC link in the synchronized AC grid, support for the frequency stability by redistributing the power flow. That means HVDC link acts as a balancing power carrier considering the frequency stability of the system. According to the Implementation Guidance Document (IGD) of ENTSO-E, all embedded HVDC links are required to have FSM and LFSM control functionalities on frequency setting requirements for embedded HVDC systems [20].

2.4 Frequency Measurement Methods in Power Systems

The frequency of the power system reflects the balance between electricity production and consumption at a give moment in time. The stability, control functions and power system protection depend on the frequency of the power system. When a large disturbance appears, the frequency must be accurately detected and measured to initiate control actions to restore the balance and keep the frequency near to the nominal value.

In electrical power systems, components from generation to end-user loads can be classified as single phase or three phase. Single-phase objects, which operate using a single phase supply, include various loads such as lighting systems, household appliances, motors, and power tools, as well as power sources such as single-phase generators and inverters. Distribution components, such as single phase transformers, and measuring and protection devices, including energy meters also fall under this category. Although single phase loads are common in residential and commercial applications, they can create unbalanced conditions in three phase networks, leading to inaccurate frequency measurements. Additionally, non-linear single-phase loads can introduce harmonics. Therefore, advanced filtering methods and detection techniques are required to maintain accurate frequency measurements of the power system.

Frequency measurement accuracy and the measuring time window are important factors that influences the performance of the different applications in the power system [21]. The RoCoF measurement for the evaluations on synchronous area level is not for immediate local protection, but rather for system-wide monitoring, controlling, planning, and analysis. As an example for a large-scale disturbance, the RoCoF on a synchronous area level is used to: assess how fast the entire area's frequency is falling, predict whether under frequency thresholds may be reached, trigger system wide controls or contingency plans if required. Table 2.2 shows the summary of the frequency measurement requirements in different applications of the power system.

Traditionally used the Supervisory Control and Data Acquisition (SCADA) systems to analyze the system behavior with typical rate of 2-4 sec fetched from the sensors. The major drawback of this system was the lack of a synchronized timestamp for the measured data, making it impossible to determine the state of the system at any given moment [22]. This issue was resolved by later technologies developed for measurements in electrical power systems.

Table 2.2: Frequency Measurement Characteristics of Different Applications [21]

Application	Measuring Time Window (ms)	Accuracy	Comments
Protection	90 - 120	30 mHz	Generation unit, Underfrequency load shedding
Local Control	100 - 200	10 mHz	Decentralised generation control
Centralized Control	500	1 mHz	Centralised generation control (AGC)
Limited Frequency Sensitive Mode (LFSM)	100	50 mHz	System control, System protection
RoCoF	180 - 240	50 mHz/s	Additional protection criteria for generation or load
RoCoF	500 - 1000	1 mHz/s	Evaluations on synchronous area level

Numerous previous studies have explored various frequency measurement methods in power systems [22] specially for frequency measurement as well as RoCoF. Most of them proposed combined or advanced approaches to mitigate individual drawbacks related to accuracy, hardware implementation, and signal quality. For example, the smoothed Taylor Kalman Filter is a combined approach based on Kalman filtering and Taylor series expansion [28]. This approach observed as computationally efficient and higher accuracy than individual methods [28]. In addition, [29], [30] and

[31] have focused on combined and advanced approaches of other methods such as Discrete Fourier Transform and Prony analysis. A novel approach based on point-on-wave technology for the measurement of future power systems specifically focusing on the Swedish power network, was studied in [24].

2.4.1 Frequency Measurement Methods at Present

Phasor Measurement Unit (PMU) is increasingly becoming the most commonly used metering device at present electrical power networks which estimates key electrical parameters, including RMS voltage and current magnitude, phase angle, frequency and the rate of change of frequency (RoCoF). These devices are used for power system monitoring and control. PMUs derive synchrophasors from AC voltage and current waveforms by sampling over a specific time window. These measurements are time synchronized to ensure consistency across multiple locations enabling precise analysis of power system performance. Figure 2.2 shows the input and output quantities of the PMU.

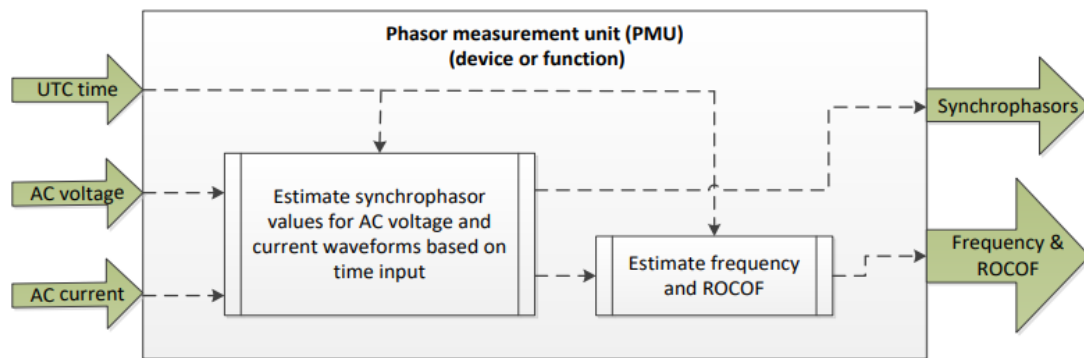


Figure 2.2: Input and Output Quantities of PMU [23]¹

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PMUs offer reporting rates as shown in Table 2.3 below. This is much higher than compared to traditional SCADA systems [24]. PMUs sample data at 128 samples per cycle at a nominal 50 Hz frequency and report as the RMS values. This allows operators to detect dynamic grid conditions more effectively and implement corrective actions before stability issues arise [24]. PMUs comprised of several filters to enhance the accuracy of the estimates. These include antialiasing filters and digital filters (P-class and M-class).

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Table 2.3: Standard PMU Reporting Rates [23]

System frequency	50 Hz			
Reporting rates (frames per sec)	10	25	50	100

PMUs facilitate for Wide Area Monitoring Systems (WAMS), which integrate data from multiple locations to provide a real-time assessment of the condition of the power system. Most common techniques used for the phasor estimation in PMUs are Discrete Fourier Transform (DFT) and its variants such as Sliding DFT [27].

The following subsection focuses on the main and widely used frequency measurement methods in the power system [22] without specifically addressing those used for specific power generation units, functions, or devices.

2.4.1.1 Zero Crossing Technique

The zero crossing technique is one of the most commonly used methods for frequency measurement due to its simplicity. It determines the frequency of a periodic signal (sinusoidal waveform) by detecting the points where the waveform crosses the zero-voltage (or zero-current) level and measuring the time intervals between these crossings.

The zero crossing can be detected by checking the signs of the adjacent samples in the digital platform. The duration between two points can be taken based on the sample count and the sampling interval. The frequency is determined as the reciprocal of the average time interval between consecutive zero-crossings [25]. Figure 2.3 shows the zero crossing detection using the digital platform.

High-frequency noise and harmonics generated due to non-linear loads and switching actions can introduce inaccuracies, making it necessary to apply low-pass filters for this method. Although this is a simple and effective approach for frequency measurement, this often needs to be supplemented with additional techniques to ensure accuracy and robustness in practical power system applications.

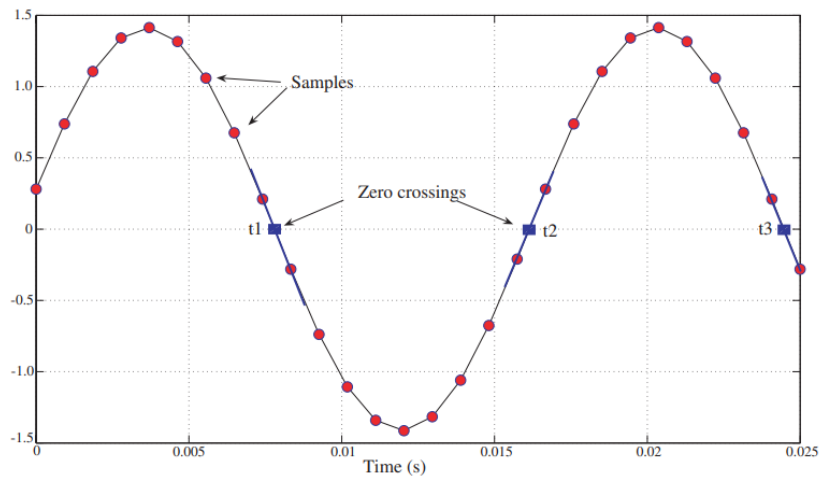


Figure 2.3: Zero crossing technique [25]

2.4.1.2 Phase Locked Loop (PLL)

A Phase-Locked Loop (PLL) is a technique that locks on to the phase of an input signal and continuously tracks its frequency. This is used for precise frequency and phase tracking in power systems. This comprised with three components; Phase Detector (PD), Loop Filter (LF) and Voltage Controlled Oscillator (VCO) as shown in Figure 2.4.

A new signal v_q is produced at the phase detector based on the input signal v_{abc} . The LF compares the error ϵ_q between v_q and the value estimated by the PLL. There are different methods in PLLs to perform filtering, including stages such as attenuation, low-pass filtering or high-pass filtering [26]. The VCO's oscillation frequency is then adjusted, and its output is feed back again as show in the Figure 2.4. With each feedback cycle, the frequency difference progressively decreases until it reaches zero, indicating that the PLL has reached its locked state [25]. The pure integrator generally consists of VCO to avoid steady-state signal noise [26].

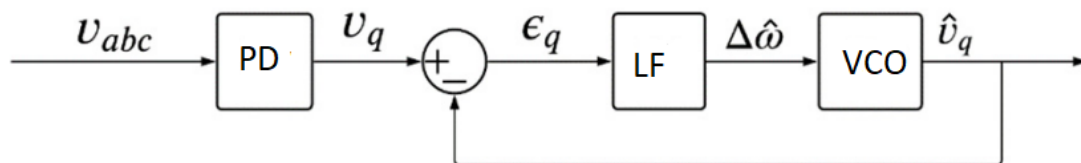


Figure 2.4: Main Components of a PLL (adapted from [26] (© 2022 by the authors. Licensed under CC BY 4.0) and modified)

Accordingly, the PLL continuously adjusts the frequency of a VCO to match the frequency and phase of an input signal. This ensures accurate frequency estimation, even in the presence of noise and harmonics. There are different PLL configurations such as synchronous reference frame PLL (SRF-PLL), Lag PLL (LAG-PLL), Low-Pass Filter PLL (LPF-PLL), Enhanced PLL (E-PLL), Moving Aver-

age Filter PLL (MAF-PLL), second-order generalized integrator–frequency-locked loop (SOGI-FLL), second-order generalized integrator PLL (SOGI-PLL), and double second-order generalized integrator PLL (DSOGI-PLL) which are used based on the applications [26].

2.4.1.3 Discrete Fourier Transform (DFT)

This is a widely used technique for frequency measurements by transforming time-domain signals into frequency-domain representations. DFT analyzes a window of sampled data to extract fundamental frequency component. Also effective in estimating phasors, which include both magnitude and phase angle information [27].

A sinusoidal signal in the time domain can be expressed as:

$$x(t) = X_m \cos(\omega t + \phi) \quad (2.3)$$

Here the X_m is the signal amplitude, ω is the angular frequency and ϕ is the phase angle. The corresponding phasor representation is give by:

$$X = X_m e^{j\phi} \quad (2.4)$$

When the signal is sampled at discrete time intervals, producing a sequence $\chi[m]$, the DFT is used to transform it into the frequency domain:

$$X(k) = (1/M) \sum_{m=0}^{M-1} x(m) e^{-j\frac{2\pi}{M} km} \quad (2.5)$$

Here M is the number of samples per cycle, k represents the frequency bin and x(m) is the sampled signal. The frequency domain, X(k) has two parts, real and imaginary. Accordingly the magnitude $|X(k)|$ and the phase angle ϕ_k are determined as;

$$|X(k)| = \sqrt{(\text{Re}[X(k)])^2 + (\text{Im}[X(k)])^2} \quad (2.6)$$

$$\phi_k = \tan^{-1} \left(\frac{\text{Im}[X(k)]}{\text{Re}[X(k)]} \right) \quad (2.7)$$

2.4.1.4 Fast Fourier Transformation (FFT)

The FFT technique enables precise calculation of magnitude, frequency, and phase angle parameters without delay [22]. The DFT method can analyze the harmonic content of a power signal by examining its amplitude spectrum. However, DFT requires significantly more time, performing N^2 complex multiplications to compute the spectrum of N input points, whereas the FFT algorithm reduces this complexity to $\frac{N}{2} \log_2 N$ making it much more efficient [22].

An example of the frequency amplitude range shown in Figure 2.5 provide the information of amplitude of frequencies with respect to the bin index (the frequency

index). The maximum value represents the fundamental frequency of the input signal.

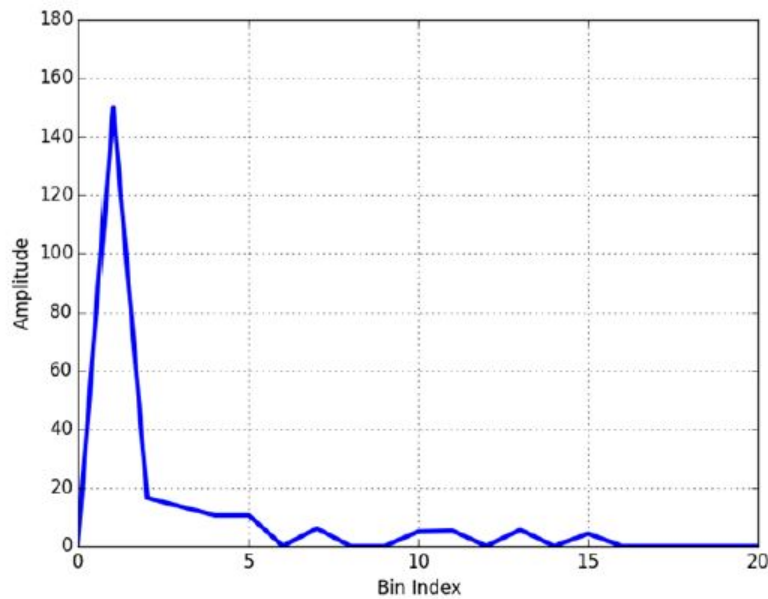


Figure 2.5: Amplitude Range of FFT [22]

The frequency f_k in Hz is calculated as;

$$f_k = \frac{k \cdot f_s}{N}$$

where k is the bin index (cycles per frame) corresponding to maximum amplitude, f_s is the sampling rate (samples per unit time) and N is the number of samples in one frame.

2.4.1.5 Kalman filtering

The Kalman filter provides real time frequency estimation by continuously updating the frequency state based the noisy measurements. The accuracy of the frequency estimation methods become lower in noisy and time-varying conditions specially with increasing penetration of renewable energy sources and dynamic loads in present as well as future power systems. The Kalman filter works based on two steps: Prediction step and Correction step. The process recursively estimates the frequency by predicting the next state and update based on new observations while minimizing the mean squared error.

Recent research has highlighted the variations of kalman filter for frequency and RoCoF estimation such as Taylor-Kalman filter [28], Bank of Kalman Filters [29] and Kalman Filtering Combined with Interpolated DFT [30]. Also mentioned the requirement for further research on advanced models based on Kalman filtering to assess the benefits, limitations, and to achieve an optimal balance between accuracy and real-time processing efficiency.

2.4.1.6 Taylor Approximation Method

The Taylor approximation method is a mathematical approach which estimates frequency in power systems using the Taylor series expansion. In this method, the power system voltage or current waveform is expressed using a Taylor series expansion. Then, taking the derivatives of the signal and relating these derivatives to the fundamental frequency component, the method derives an estimate of the frequency of the signal.

This method has been enhanced by introducing filtering techniques and correction mechanisms for dc offset removal through enhanced algorithms [31]. This is called the improved Taylor approximation method. One of the key features of the algorithm is a good tracing ability for the frequency change in a power system [31].

2.4.1.7 Prony Estimation Method

Prony analysis is a signal processing technique used to estimate the fundamental frequency in power systems. Recent research presents an advanced approach using Complex Prony Analysis (CPA) to improve accuracy in dynamic conditions [32]. This novel method, extends traditional Prony analysis by directly working with complex signals (real and imaginary components).

This method is identified as more robust against the noise and transient disturbances. Also suitable for steady-state and dynamic conditions in power grids.

2.4.1.8 Least Square Error (LSE) Technique

The LSE technique is a regression-based method used to estimate phasors as well as frequency in power system applications. This method is particularly effective in noisy environments, where it minimizes the sum of squared errors between the measured and estimated values. LSE is widely used in power system applications due to its robustness in handling signal distortions and harmonics.

The fundamental principle of LSE is to approximate an unknown function $f(x)$ by minimizing the sum of squared deviations between the actual measured values and the estimated values. This can be expressed as:

$$E = \sum_{i=1}^N \epsilon_i^2 = \sum_{i=1}^N (y_i - \hat{y}_i)^2 \quad (2.8)$$

Where E is the sum of the squared errors, y_i is the measured value, \hat{y}_i is the estimated value and N is the number of the data points.

2.4.2 Future Trends and Requirement of Frequency Measurement Methods

The Nordic power system historically dominated with the large synchronous generators connected to the grid. This has undergone a change recently and to be further

change in future with increase of variable renewable energy based power generation for the power system. Therefore, the future of the Nordic power system will be dominated by power electronic based components.

These power electronic inverters introduce oscillations, including high-frequency oscillations and resonances across a broader frequency spectrum to the power grid. In addition, those do not have inherent oscillation damping properties as synchronous generators [24]. Further, there will be fast ramp up and downs as well as fast changes (higher variability) of the frequency due to the reduction of system inertia and higher production variability. Therefore, current measurement methods used in the power system applications such as PMUs will not be adequate to detect the disturbances and monitor the system behavior in future. This will result in the requirement of system monitoring and control methods with higher frequency ranges. Waveform based measurement is identified as the potentially best method for the power electronics based power systems [35].

2.4.2.1 Point On Wave Technology

The Point of wave technology is the method used in Waveform Measurement Units (WMU). This advanced measurement system is used in power grids to capture and analyze real-time voltage and current waveforms at high resolution. Unlike present Phasor Measurement Units (PMUs) that rely on RMS based measurements, WMUs use point-on-wave technology which records magnitudes (voltage and current) at set time intervals. This allows WMUs to provide a more detailed and accurate representation of electrical waveforms by making these essential for power electronic dominated modern power systems [24]. WMUs are typically implemented in Wide Area Monitoring Systems (WAMS) to enable synchronized monitoring across multiple locations. This synchronization allows operators to track how disturbances propagate through the grid, improving the detection of grid instabilities.

The use of the RMS based measurement method in power electronic dominated power system will result for the wrong interpretation of the system conditions such as classification of oscillations as sub-synchronous even when they may actually be super-synchronous [24]. Also, for higher-frequency oscillations exceeding 100 Hz, RMS-based systems are insufficient. In such cases, waveform measurement becomes crucial, requiring a reporting rate of approximately 2000 Hz to accurately detect a broader range of potential disturbances [24].

According to the above, adopting waveform-based measurement techniques is important to effectively monitor future disturbances in the Nordic power grid. While current RMS-based methods can detect sub-synchronous oscillations, they may misinterpret super-synchronous or high-frequency oscillations as sub-synchronous. Even with increased RMS reporting rates, these methods remain inadequate for capturing future high-frequency disturbances.

2.4.3 Comparison of Frequency Measurement Methods

Table 2.4: Frequency Measurement Methods Comparison

Method	Advantages	Disadvantages	Typical Uses and Commercial Products
Zero Crossing Technique	Simple and easy to implement	Incapable of making fast estimates using polluted signals [32], Performance is sensitive to switching type transients [32]	Basic frequency detection in low-noise environments
Phase Locked Loop (PLL)	Capable of real-time frequency tracking	Performance degrades in weak or noisy grids	Synchronization of inverters, converters, HVDC systems, Protection Relays. Commercially use in L90 Line Differential Relay of GE Power Management [36]
Discrete Fourier Transform (DFT)	This can be used to estimate fundamental frequency, phasor and harmonics [25]	Leakage error effect causes due to the sampling rate of the design will impact on the phasor and frequency estimation [25], Need to have compensation techniques for good accuracy [25]	Phasor and Frequency estimation [25]. Use in PMUs and Protection relays. Commercially use in Hitachi Energy Phasor Measurement Unit RES670 (Relion 670 SERIES) [38], ABB REL670 series for Line Distance Protection [37]
Fast Fourier Transform (FFT)	Effective for detecting harmonics and spectral components	Requires high computational power, not ideal for real-time applications	Power quality analysis, harmonic detection
Kalman Filtering	Enables direct control of RoCoF with high accuracy [30]	Significant delays in measurements [25], sensitive to initial conditions [32], performance varies with internal model parameters [32]	Power system frequency and RoCoF estimation [30]
Taylor Approximation Method	Simple but efficient algorithm, Low computation requirements, Suitable for hardware implementation [31]	The algorithm is restricted to the sampling rate at a specific value [31], Not capable of providing measurements over a wide range of frequencies [31]	Measurement of Frequency and RoCoF [31]
Prony Estimation Method	Identification of the damping factor of each mode in the signal, Identification of transient harmonics accurately [33]	Computational complexity, Accuracy depend on the input signal quality [33]	Estimate frequencies, magnitudes, phases, and especially damping factors of exponential decaying or growing transient harmonics [33]
Least Square Error (LSE) Technique	Simple technique [34]	Computational complexity, Inaccurate estimation of decaying dc component (causes mal operation of distance relays) [34]	Power system phasor and frequency estimation [27]
Point on wave technology (Method used in WMTU)	Higher sampling rate (up to 12.8kHz), Enable to capture a broader range of power system phenomena [24]	Requires high storage, Required efficient data transfer method, Possibility of slow response [24]	Future power systems driven by power electronics to efficiently identify a broader range of disturbances [24]. Commercially use in Hitachi Energy Switch-sync PWC600 Point-on-wave Controller(Several product models are available for addressing different application needs such as circuit breakers, power transformers, capacitor banks, shunt reactors and power transmission lines)

3

Comparison of Normal Frequency Bandwidths of Countries and Regions

During the normal operation of power networks, the frequency is allowed to fluctuate within a specific range established in the grid codes by the national transmission system operator or power system regulator.

3.1 Normal Operational Frequency Range Comparison

Table 3.1 presents a comparison of the normal operational frequency ranges of different countries and regions.

Table 3.1: Normal Frequency Range of Different Countries and Regions

Country/Interconnection	Nominal Frequency (Hz)	Normal frequency (Hz)	Frequency Range	Deviation (%)
Continental Europe [41]	50	49.95 - 50.05		+/- 0.1
Nordics [40]	50	49.90 - 50.10		+/- 0.2
Australia [42]	50	49.85 - 50.15		+/- 0.3
Japan (Eastern) [46] : Tokyo, Tohoku	50	49.80 - 50.20		+/- 0.4
Ireland [40]	50	49.80 - 50.20		+/- 0.4
China [40]	50	49.80 - 50.20		+/- 0.4
Japan (Eastern) [46] : Hokkaido	50	49.70 - 50.30		+/- 0.6
India [44]	50	49.50 - 50.20		+/- 1 / +/- 0.4
Great Britain [39]	50	49.50 - 50.50		+/- 1
Sri Lanka [43]	50	49.50 - 50.50		+/- 1
Eastern Interconnection (US) [45]	60	59.95 - 60.05		+/-0.083
Western Interconnection (US)[45]	60	59.856 - 60.144		+/-0.24
Japan (Western) [46]	60			
Chubu, Shikoku, Kyushu	60	59.80 - 60.20		+/- 0.33
Okinawa	60	59.70 - 60.30		+/- 0.5

In addition to the above, Table 3.2 shows the maximum frequency variation allowed for the grid of the different countries.

Table 3.2: Grid Frequency Variation Range

Country/Interconnection	Nominal Frequency (Hz)	Grid Frequency Range (Hz)
Great Britain [39]	50	47.0 - 52.0
Nordics [59]	50	47.5 - 51.5
Australia [42]	50	47.0 - 52.0
Sri Lanka [43]	50	47.0 - 52.0
Eastern Interconnection (US) [45]	60	57.0 - 61.8
Western Interconnection (US)[45]	60	57.0 - 61.8

3.2 Influencing Factors for Different Frequency Bandwidths

Transmission system operators or regulators decision to maintain a tight or flexible normal frequency bandwidth of different countries or regions are dependent on several important factors such as nature of generation characteristics, network operation requirements, technical requirements as well as economic limitations [40].

3.2.1 Main factors result for the tight normal frequency bandwidth of the power networks

According to Table 3.1, countries or regions which have frequency band equal or less than $\pm 0.2\%$ are the Eastern interconnection of US, Continental Europe and Nordic countries. Below discuss the main reasons for those countries or regions to have tight frequency band considering their present power system.

- Large synchronous generation with high system inertia

Eastern interconnection of US consists of many thermal, nuclear, and hydro power plants, which provide high system inertia. Nordic countries operate in an interconnected synchronous system which has a high share of hydro power supporting fast frequency response with high system inertia. Therefore, a tighter frequency range is feasible because the system can quickly adjust generation to match load variations.

- High and Sensitive Industrial Loads

Both the Eastern US and the Nordic countries have high concentrations of industrial facilities such as steel, aluminum, paper, chemical etc. for the Nordic region [47]. These industries comprised with continuous processes as well as sensitive equipment which required stable frequency. Therefore, these countries kept tighter frequency

margin for the variation under the normal conditions of the power system.

- Regulatory & Market Structure

Strict frequency controls of these regions will minimize unscheduled power flows, overloaded transmission lines and grid instability. This ensures fair competition among power producers and prevents entities from frequency deviations.

3.2.2 Main factors result for the flexible normal frequency bandwidth of the power networks

According to the Table 3.1, the countries or regions which have frequency band higher than $\pm 0.2\%$ are the Western interconnection of US, Japan, China, Australia, India, Sri Lanka etc. Below discuss the main reasons for those countries or regions to have relatively flexible frequency band considering their present power system.

- Relatively smaller power systems

This is directly related to the Western interconnection of US, which is geographically large, but the power system is small compared to the Eastern interconnection [32]. Therefore, the Western interconnection has lower system inertia resulting in more frequency fluctuations at normal system conditions. Slightly wider normal frequency range prevents unnecessary emergency actions and keeps the grid stable without excessive intervention.

- Isolated power systems (Lower Grid Interconnections & External Support)

This is more relevant for the countries such as India, Sri Lanka and for the Western interconnection of US. When a country or a region has limited ties to other grids, it cannot rely on external power sources for frequency stabilization. A wider frequency band allows for more self-balancing without constant load-shedding or generator ramping.

- High Renewable Energy Penetration

Wind and solar are variable and intermittent, making the frequency control more challenging. Therefore, the country like Australia allows flexible frequency band to absorb fluctuations without frequent need for reserves or backup generation.

- Cost & Infrastructure Constraints

Tight frequency control requires expensive infrastructure, such as automated frequency response systems and energy storage technologies. Therefore, allowing frequency fluctuations within a wider range is standardized in some countries or regions, rather than investing in costly control mechanisms.

3. Comparison of Normal Frequency Bandwidths of Countries and Regions

4

Sensitive Power System Components to Frequency Fluctuations

This chapter focuses on the requirement of maintaining the proper frequency values in the power system and explores the components of the power system involved in generation, transmission, distribution, and load, which are sensitive to frequency fluctuations.

4.1 Requirement of the Proper Frequency Value in Power Systems

The standardization of power system frequencies at 50 Hz or 60 Hz was influenced by various historical, technical, and economic factors specific to different countries or regions. According to [49], power system frequencies in America have historically varied, including $133 \frac{1}{3}$, 125, $83 \frac{1}{3}$, $66 \frac{2}{3}$, 60, 50, 40, 30, and 25 cycles per second. Factors or equipments such as incandescent lighting, transformers, transmission systems, arc lighting, induction motors, synchronous converters, construction constraints in rotating machinery, and operating conditions played a crucial role in determining the frequency of the power supply system in America [49].

In present power grids with the operation of large-scale synchronous generators, the requirement of maintaining the standard power system frequency (50Hz or 60Hz) is still important. This is mainly due to the rotational cycle and operational efficiency of the connected synchronous generators. However, electrical power supply systems for certain industries and applications within these major power grids require different nominal frequencies based on equipment design and efficiency. For example, the Swedish railway power supply system operates at a frequency of 16.7Hz [50].

The future power networks, increasingly dominated by power electronic based devices and converters rather than large scale synchronous generators, will allow systems to operate at different frequencies with high flexibility other than standardized nominal frequencies of 50Hz or 60Hz. However, in such a scenario, comprehensive studies on factors such as infrastructure compatibility, regional compatibility, and investment requirements will be essential, alongside considerations of power system operational aspects.

4.2 Sensitive Power System Components for Frequency Fluctuation

Power system components can be categorized based on their use in power generation, transmission and distribution and load side. A wide range of research has been conducted to examine the effects of frequency deviations on these sensitive components. The impact on the normal frequency deviation on power plants and the load side is discussed in [53] focusing on the North American power system. This study highlights how slight frequency variations can influence generator output, turbine performance and consumer loads. In addition, [55] and [56] discuss the impacts of frequency deviations on protection relays and inverter based generations respectively. The load side components and their dependency on the power system frequency have been studied in [58].

This section of the report has focused on the components of the power system in generation, transmission, distribution and load side that are sensitive to the frequency fluctuation from the nominal value and their limit setting criteria.

4.2.1 Components in Power Generation Side

The power generation side components that are sensitive to frequency fluctuations from the nominal value mainly include the turbine and the generator, where the turbine is generally more sensitive to such variations. Below discussed the components and their general and standardized settings and limits relevant for the power system frequency fluctuation.

4.2.1.1 Turbine at Under and Over Frequency Operation

When the power system operates slightly below or above the nominal frequency, turbines may enter one of their natural frequencies leading to accelerated metal fatigue [52]. This concern applies specifically to steam and combustion turbines. Modern combustion turbines have reduced tolerance to frequency variations due to the reduced limits by efficiency driven design changes. Turbine manufacturers provide under and over frequency operation curves with allowed regions to operate and maximum accumulated time for the unit operate during the lifetime. Figure 4.1 presents an example for the machines in a 60Hz system.

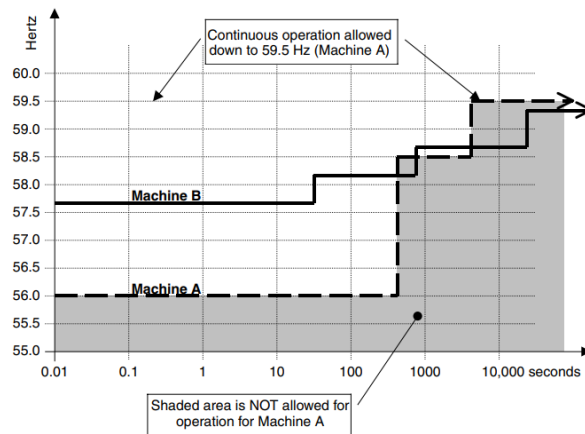


Figure 4.1: Under frequency operation curves of turbines [52]. Republished based on the license agreement between the author and Copyright Clearance Center, Inc. (“CCC”) on behalf of the Rightsholder John Wiley & Sons - Books, ISBN-13: 9780471614470. Order License ID: 1615559-1

Direct protection for this is done by the sensing of speed and load conditions while indirectly done through the over and under frequency protection scheme.

4.2.1.2 Generator Volts-per-Hertz Limit

For the generator, the primary concern is that when operating at the lowest frequency and the maximum allowable terminal voltage, the machine could exceed the allowed range of V/Hz. The Volts-per-Hertz ratio of a generator defines the flux density in the generator core and this is proportional to the heat losses [53]. Figure 4.2 shows the voltage-frequency limits identified by IEC 60034-1 for industrial generators and required to be designed to operate within the minimum V/Hz ratio.

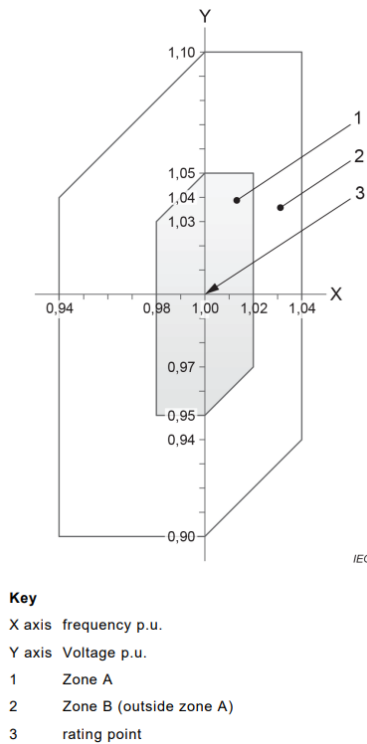


Figure 4.2: IEC 60034-1 Voltage-Frequency Limit [54]²

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The high ratio of volts-per-hertz will cause overheat of the generator core laminations. When the generator becomes over fluxed by exceeding the permissible limits or exceeding the maximum V/Hz, it may cause complete failure of the core in a short time, or after some time of operation [52]. This condition should be handled by the protection scheme that focuses on the reduction of the terminal voltage or the removal of the unit from operation [52].

4.2.1.3 Generator Capability Curve and Related Constraints

The synchronous generator capability curve significantly impacts its performance during frequency fluctuations. This is because the curve defines the operating limits of the generator in terms of active and reactive power, thermal constraints, and stability margins. When the frequency fluctuates, the generator must adjust its output to help stabilize the grid and its performance will be constrained by the capability curve. The frequency variation of the power system has an impact on the core losses of the armature. Specially, higher frequency will increase the eddy current and hysteresis losses by resulting in overheating of the armature. Therefore, the generator performance will be constrained by the core-end heating limit. Also, the

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grid frequency variation may cause variations in the load angle of the machine, which affects its transient stability. At lower frequencies, the field current must increase due to the decreased rotor speed to maintain the terminal voltage. This will affect for the field current limit of the capability curve. Figure 4.3 presents the capability curve of a generator with the turbine and power system stability constraints.

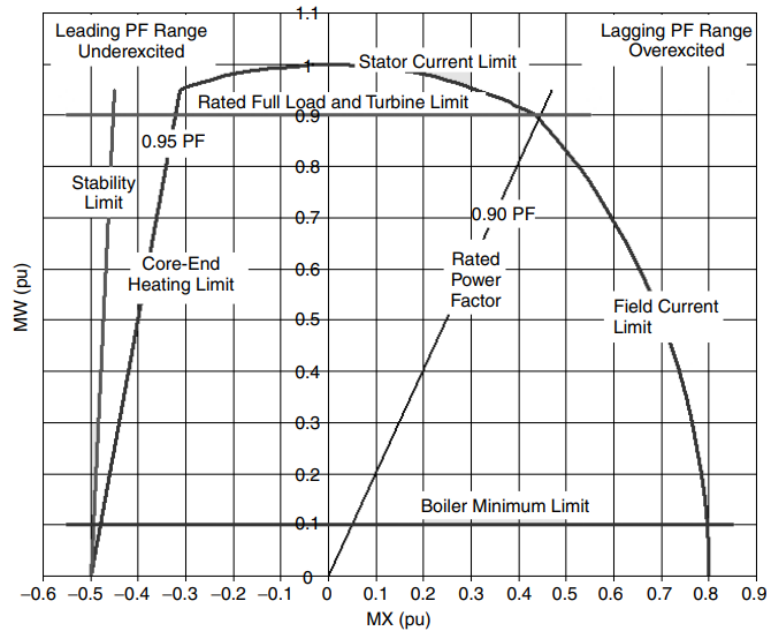


Figure 4.3: A Generator Capability Curve. MW in Y axis [52]. Republished based on the license agreement between the author and Copyright Clearance Center, Inc. (“CCC”) on behalf of the Rightsholder John Wiley & Sons - Books, ISBN-13: 9780471614470. Order License ID: 1615559-1

4.2.1.4 Power Plants Auxiliary Systems

Typical components of the auxiliary system of the power plant comprised with induction motors to drive essential components such as pumps and fans, auxiliary transformers, UPS and battery systems, etc. Induction motor operating speeds are directly proportional to power supply frequency, and fluctuation will result in reduced cooling, increased heating, and a decrease in torque, affecting critical operations such as boiler feed pumps, cooling water pumps, and fans. Induction motors are capable of operating continuously under the rated output conditions at any frequency between 95% and 105% of the rated frequency. Auxiliary transformers are also affected by frequency fluctuations due its Volts-per-Hertz Limit. Transformers are generally capable of withstanding over-fluxing conditions caused by combined voltage and frequency fluctuations, with 110% for continuous operation, 125% for one minute, and 140% for five seconds [51].

4.2.1.5 Sub-Synchronous Resonance (SSR) Risks

SSR is a potentially destructive phenomenon that occurs when off-frequency currents in a power system interact with the natural torsional frequencies of a turbine-generator shaft, leading to damaging mechanical vibrations. These off-frequency currents can be caused by transformer saturation, harmonic currents, or series capacitor compensation in long transmission lines. If the frequency of the induced pulsating torque aligns with a torsional mode of the shaft system, it can result in severe stress, fatigue damage, and even catastrophic failure of the generator or turbine components. Predicting SSR is challenging due to the difficulty in accurately identifying higher natural frequencies, and while the likelihood of occurrence is low, its consequences can be severe. Real-world incidents, such as generator shaft failures in California, highlight the risks associated with SSR [52].

To mitigate these risks, SSR filters and adaptive compensation techniques are used to suppress harmful oscillations and prevent resonance conditions [52].

4.2.2 Components in Power Transmission and Distribution Side

Frequency fluctuations in a power system can significantly affect various components on the power transmission side, particularly those that rely on a stable frequency for proper operation. The most vulnerable components are transformers, transmission lines and protection relays.

4.2.2.1 Transformer with Volts-per-Hertz Limit

Similar to the discussion in subsection 4.2.1.2 regarding generators, the volts-per-hertz ratio affects the transformer core flux density [52]. This is because the maximum flux density in the core of a transformer is proportional to the volts-per-hertz ratio (terminal voltage divided by the frequency of the supply voltage).

$$B_{\max} \propto \frac{V}{\text{Hz}} \quad (4.1)$$

Lower frequency than the nominal value will increase the volts per hertz ratio will increase the flux above the knee of the saturation curve. This resulted in higher magnetizing current and increase of the core and copper loss. Prolonged frequency variations can degrade insulation materials due to overheating by shortening the useful life of the transformer. In addition, a reduction in the transformer efficiency will result due to the change in the optimal operating point.

4.2.2.2 Transmission Lines

With the frequency fluctuation of the power grid, various generators connected to the system try to restore the frequency to the nominal value. This may overload the transmission lines of the network [53]. This results in the increase in the line losses by reducing the line efficiency. In addition, the variation in current flow leads

to uneven heating and cooling cycles in transmission lines. This thermal stress can accelerate conductor aging, increasing the risk of failures and outages.

4.2.2.3 Protection Relays

Frequency fluctuations significantly impact protection relays by introducing errors in phasor estimation, filtering and impedance calculations [55]. Since relays rely on accurate phasor measurements to detect faults, deviations from the nominal frequency cause oscillations in estimated magnitudes, leading to momentary overestimation or underestimation of system parameters [55]. These fluctuations also affect filters and sampling processes, which are designed for a fixed frequency, causing misalignment in sampled data and potential malfunctions. Harmonic distortions further degrade the performance of the relay, as filters tuned to the nominal frequency may misinterpret signals, leading to incorrect fault detection.

The overcurrent and distance protection relays are affected when the overcurrent relays can potentially fail incorrectly due to miscalculated current magnitudes, while the distance relays can suffer from errors in impedance measurement, resulting in incorrect fault zone identification [55]. In general, these impacts can lead to maloperations, delayed fault clearing, and compromised system reliability, highlighting the need for adaptive protection schemes that can account for frequency variations.

4.2.2.4 Inverter Based Resources with Grid Following Inverters

Inverter based resources with grid following inverters are sensitive to frequency fluctuations, which can lead to synchronization issues, inefficiencies, and disconnections. Grid following inverters utilize PLL controllers to align with the frequency of the grid [56]. Sudden frequency deviations of the grid can disrupt this synchronization, leading to unstable operation or inverter tripping.

4.2.3 Components in Load Side

Among other issues such as voltage sag, interruptions, voltage fluctuations, harmonics, the power system frequency fluctuation also can reduce the power quality. The frequency fluctuation of the power system has a high impact on the components on the load side, especially for industrial loads, steel mills, pumps and aluminum refineries.

4.2.3.1 Motors

Typically major part of the total energy of the power grid is consumed by the motors [57] which are sensitive for the frequency variation. Generally, 1% decrease in frequency can lead to a 2% reduction in motor load [58]. This sensitivity affects industrial processes, air conditioning systems, pumps, compressors and many other applications reliant on motor driven equipments. However, some of the large

industries use variable frequency drives as motors control in their industrial processes [53]. Most variable frequency drives are unaffected by supply frequency and accurately control their output frequency. As a result, systems utilizing variable frequency drives remain stable despite minor fluctuations in power system frequency [53].

4.2.3.2 Other Electronic Equipment

In the present context there is a large number of electronic equipment in consumer end. All of these rectify the incoming AC power by converting to DC. The converters used for rectification are not sensitive to frequency variations within a range of $\pm 5\%$ [53].

4.3 Discussion of the Nordic Power System

This section has focused on the discussion of the Nordic power system, especially with regard to the limits adopted for the different components of the power system and their associated protection equipment.

4.3.1 Generation Components Specific Frequency Limits

There are special requirements mentioned for the grid connection of the generators in ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators. This is based on the EU regulation 2016/631 considering the new power generating modules and applicability of the existing generation facilities to be decided by the relevant TSO of the member state [59]. Table 4.1 present the generator categorization, voltage level of connection and capacity applicable for the Nordic region.

Table 4.1: Type A, B, C and D Power Generating Modules [59]

Power Generating Module Type	Connection Voltage	Capacity
A	Below 110	≥ 0.8 kW
B	Below 110	≥ 1.5 MW
C	Below 110	≥ 10 MW
D	Above 110 or Below 110	≥ 30 MW

According to the article 8 of [59], the power generation module should be able to stay connected to the network and operate within specified frequency ranges and time periods. This information relevant for the Nordic synchronous ares is shown in Table 4.2.

According to [60], the Danish utility regulator defines the minimum 30 minutes for the 48.5 Hz - 49 Hz frequency range. In addition, the total operation time below 49 Hz is defined to not exceed 60 minutes.

Table 4.2: Nordic Region Frequency Limits and Time Constraints

Frequency Range (Hz)	Time Limit
47.5 – 48.5	30 minutes
48.5 – 49.0	Defined by each TSO, but not less than 30 minutes
49.0 – 51.0	Unlimited
51.0 – 51.5	30 minutes

4.3.1.1 RoCoF Limits

The RoCoF withstand capability of the power generation module and loss of main detection to be defined by the relevant TSO. Accordingly, the defined values for Denmark approved by the Danish Utility Regulator are as shown in Table 4.3 .

Table 4.3: Rate of Change of Frequency (ROCOF) Limits

Parameter	Value / Condition
ROCOF	2.0 Hz/s
ROCOF – Tripping Over-frequency	If calculated ROCOF value is $> +2.5$ Hz/s for more than 80 ms
ROCOF – Tripping Under-frequency	If calculated ROCOF value is < -2.5 Hz/s for more than 80 ms

4.3.1.2 Limited Frequency Sensitive Mode – Overfrequency (LFSM-O) and Frequency Sensitive Mode – Underfrequency (LFSM-U)

The LFSM-O function ensures that the generating units reduce their active power output when the system frequency rises above the nominal (50 Hz) to help stabilize the grid. Below are the details for the Type A, B, C, and D generation modules as specified in [59].

Table 4.4: LFSM-O Limits [59]

Type	Activation Frequency	Droop Setting Range	Response Time	Additional Requirements
A	51.5 Hz – 50.5 Hz	2–12%	As fast as technically feasible (Initial delay max 2 sec, but justifiable if longer)	<ul style="list-style-type: none"> Active power reduction should continue down to Minimum Regulating Level or further, as defined by the TSO.
B	51.5 Hz – 50.5 Hz	2 – 12%	Same as Type A	<ul style="list-style-type: none"> Must maintain stable operation during LFSM-O mode. LFSM-O settings take priority over normal power setpoints.
C	51.5 Hz – 50.5 Hz	2 – 12%	Same as Type A	<ul style="list-style-type: none"> Should be able to adjust active power set point as instructed by the TSO. Higher level of controllability.
D	51.5 Hz – 50.5 Hz	2 – 12%	Same as Type A	<ul style="list-style-type: none"> Same as Type C.

In addition to above, LFSM-O must be activated automatically when frequency exceeds the defined threshold and LFSM-O takes precedence over other active power setpoints [59].

Active power reduction from maximum output under the falling frequency of Type A generating module has defined as follows;

- Below 49 Hz falling by a reduction rate of 2% of the Maximum Capacity at 50 Hz per 1 Hz Frequency drop;
- Below 49.5 Hz by a reduction rate of 10% of the Maximum Capacity at 50 Hz per 1 Hz Frequency drop

Applicability of this reduction has limited to a selection of affected generation technologies and also be subject to further conditions defined by the Relevant TSO [59].

The LFSM-U function ensures that generating units increase their active power output up to the maximum capacity when system frequency falls from nominal (50 Hz) to help stabilize the grid. Table 4.6 provide the details as specified in [59].

Table 4.5: LFSM-U Limits [59]

Type	Activation Frequency	Droop Setting Range	Response Time	Additional Requirements
C	49.5 Hz – 49.8 Hz	2 – 12%	As fast as technically feasible (Initial delay max 2 sec, but justifiable if longer)	<ul style="list-style-type: none"> Actual Frequency threshold and Droop settings shall be determined by the Relevant TSO.
D	49.5 Hz – 49.8 Hz	2 – 12%	Same	<ul style="list-style-type: none"> Actual Frequency threshold and Droop settings shall be determined by the Relevant TSO.

In addition to the above, several requirements were mentioned in the [59] when power generation modules operating in Frequency Sensitive Mode (FSM).

The operation of power generation side components under frequency fluctuation in Nordic power system should comply with the ENTSO-E grid code requirements as well as the requirement of the Nordic TSOs. Manufacturers of generators, turbines, shaft systems etc. provide component information with respective operation and performance curves. According to the [60], the generation facility owner must ensure that the facility is dimensioned and equipped with the necessary protective functions. In ENTSO-E Network Code for Requirements for Grid Connection emphasized the requirement of protection schemes for the generation modules over the protection against inadmissible shaft torsions (e.g. sub-synchronous resonance), over-fluxing (V/f) and RoCoF.

4.3.2 Transmission and Distribution Components Specific Frequency Limits

As discussed in 4.2.2.1, power transformers can be susceptible to the combined effects of high voltage and low frequency. In such cases, excessive flux can lead to intolerable core heating. This must be considered in the transformer's design. According to the IEC 60076-1 for power transformers, the transformer must be capable of operating continuously without sustaining damage under over-fluxing conditions, where the voltage-to-frequency ratio exceeds the rated value by up to 5%.

The performance of high-voltage overhead lines in transmission networks is influenced by frequency deviations because of how line parameters (like impedance and power flow) respond to frequency changes. Typically, most transmission lines are designed to tolerate grid frequency fluctuations within broader limit without any issue.

Transmission lines are typically protected by line differential relays and/or distance relays, complemented by teleprotection schemes such as Permissive Underreach Protection (PUP), Permissive Overreach Protection (POP), Accelerated Underreach Protection (AUP) and Blocking Overreach Protection (BOP) [61]. These relays also have operational frequency limits typically $\pm 10\%$ to the rated frequency.

According to [59], there are frequency limits to be considered for Power Park Modules (PPM). Categorization of Type A,B,C and D applicable same as Table 4.1 and also the frequency limits and time constraints are the same as in Table 4.2. In addition to the RoCoF limits in Table 4.3, LFSM-O in Table 4.4 and LFSM-U in Table 4.6, Type C and D power park modules shall provide synthetic inertia to the network during the low frequency event.

4.3.3 Load Side Components Specific Frequency Limits

Nordic region shows the highest electricity consumption per capita compared to Europe and the World [62]. The highest electricity consuming sector is the industry sector while the rest is shared mainly among the residential, commercial and public services and transport sectors. Figure 4.4 shows the final electricity consumption by sector for the Norway in 2022. Steel, aluminum, pulp and paper, mining and chemical are the major industries in this region.

Electricity final consumption by sector, Norway, 2022

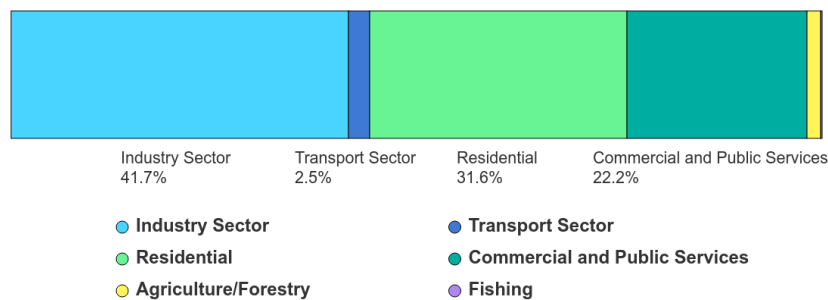


Figure 4.4: Final Electricity Consumption by Sector 2022, Norway [62]

According to the above, load side components mainly comprised with industrial motors and drives, industrial heating applications, power electronics and IT equipment, residential applications etc. Although exact frequency limits can vary based on equipment design and manufacturer specifications, general and standardized values for main load-side components in Nordic region are discussed below.

According to the IEC 60034-1, voltage and frequency variation tolerance for the induction motors are shown in Figure 4.5.

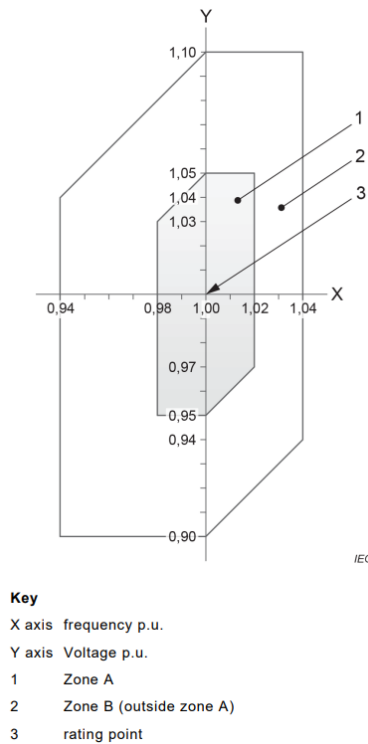


Figure 4.5: Limits of Voltage and Frequency Variation [54]³

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A motor operates continuously in Zone A while performing its main functions. It can also function in Zone B; however, performance deviations may be greater than those in Zone A when compared to the rated voltage and frequency characteristics. Additionally, temperature increases may exceed those observed at rated voltage and frequency and could be higher than those in Zone A. Prolonged operation in Zone B is not recommended [63]. Accordingly, 50Hz rated motor performance is bounded by operating frequency limit of 49Hz to 51Hz. Based on this, the centrifugal fans, pumps and all the equipment driven by the induction motors will limit the operation with the above frequency range.

In the most promising industries of the Nordic power system, electric boilers are utilized for steam generation. Manufacturer data sheets indicate a standard operating frequency of 50 Hz, although the specific frequency range is not disclosed. The Nordic industrial sector includes steel manufacturing facilities that rely heavily on electric arc furnaces, which are dependent on the electrical power system. According to major manufacturers of these furnaces, the typical operating frequency is indicated as 50 Hz. However, the tolerance limits for frequency variations are not specified.

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The Nordic industrial sector is currently being opened up to the production of green hydrogen through water electrolysis. There are different types of electrolyzers existing at the market such as PEM (Proton Exchange Membrane), Alkaline, Anion Exchange Membrane (AEM) and Solid Oxide Electrolyzers (SOE) [64]. PEM electrolyzers offer high power efficiency and low capital costs compared to the other types [64]. According to the information from manufacturers, the operational frequency of a PEM electrolyzer is 50 Hz with a tolerance limit of $\pm 5\%$ [65].

Power electronic applications in the industries like chemical, metal, mining, pulp & paper and data centers varied from power converters and inverters, drives, ups etc. According to the [6], SS-EN 60146-1-1 standard specifies requirements for the performance of rectifiers, inverters, DC/DC converters and AC/AC converters. However, there is no specific range for the operational frequency. The most sensitive equipment for frequency deviation is rectifiers and frequency drives [6]. According to the manufacturer data sheet for the industrial frequency drive the rated input frequency range given as $\pm 5\%$ for the rated frequency of 50 Hz [6]. Also for the UPS the rated frequency range is given as $\pm 10\%$ [66].

4.4 Summary

According to the above discussion, details of the frequency sensitive components can be summarized as follows.

Table 4.6: Summery of Frequency Sensitive Power System Components

Component	Frequency Sensitivity	Description of Limits
Power Generation, Transmission and Distribution Side		
Generators	Highly sensitive	V/Hz limit, Capability Curve and Related Constraints
Turbines	Highly sensitive	Underand over frequency operational curves
Power Plant Auxiliary System	Sensitive	Manufacture based standard limits
Transformers	Sensitive	V/Hz limit
Transmission Lines	Less sensitive	No specific limit and allowed broad tolerance
Relays	Sensitive	Manufacture based standard limits
Inverters	Less Sensitive	Manufacture based standard limits
Load Side		
Motors	Sensitive	Manufacture based standard limits
Converters	Less Sensitive	Manufacture based standard limits
Frequency Drives	Less Sensitive	Manufacture based standard limits
Electrolyzers	Sensitive	Manufacture based standard limits
UPS	Less Sensitive	Manufacture based standard limits

5

Model Development

This chapter presents the introduction of the PSSE Nordic 44 model, a description of the model enhancements made to match the current Nordic power system, and the simulation outputs of the PSSE model validation for the scenarios.

5.1 Introduction of Nordic 44 Model

Numerous studies have been conducted utilizing the PSSE Nordic 44 model as a foundational framework for analyzing the Nordic power system. A comprehensive discussion on the development and structure of the Nordic 44 test network is provided in [67], offering insights into its role as a benchmark model for power system studies in the region. Furthermore, the necessity of enhancing the original Nordic 44 model to reflect the current configuration and dynamics of the Nordic power system has been thoroughly examined in [69] and [70]. These studies address different power system phenomena relevant to Nordic region and emphasize the importance of updating model parameters to accurately represent present conditions.

Key areas of modification include adjustments in the total installed generation capacity categorized by energy source, updates to HVDC interconnections, revisions of the actual power production data by source and changes in electricity consumption. These enhancements ensure that the model remains relevant and reliable for the present power system validation as well as the future power system analysis.

Nordic 44 model is a consolidated simulation model developed to study the dynamic behavior of the Nordic power system. This was initially developed as Nordic 15 model at The Norwegian University of Science and Technology (NTNU) and undergone through several changes to become current state. Nordic 15 model is not an aggregated model of the Nordic power system and comprised only the buses of Norway and Sweden. It was later expanded into the Nordic 18 and further developed to Nordic 23 network model. The Nordic 44 network model developed from the Nordic 23 model. Initial model was linked with the real data provided by Statnett through STRI in cooperation with NTNU [67].

The original version of the Nordic 44 model used in this study included 44 busbars, 36 loads, 43 synchronous generators, and 7 HVDC interconnections. Also, the voltage levels are 420 kV, 300 kV and 135 kV. The Nordic 44 model with separation between price areas is shown in Figure 5.1.

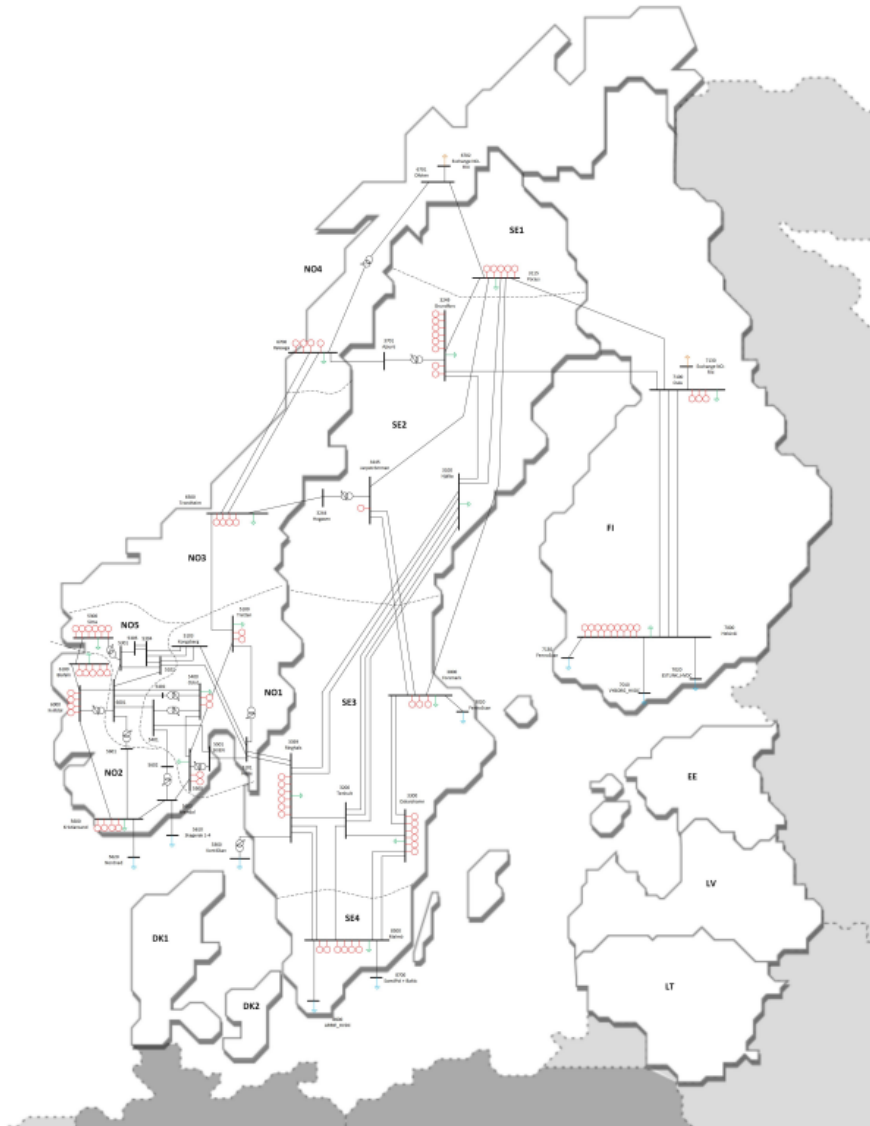


Figure 5.1: The Nordic 44 Aggregated Network Model with Price Areas [68]

5.2 Description of Model Enhancement

5.2.1 Upgrade of Voltage Levels, Busbars and Transmission Lines

The original version of the Nordic 44 model was developed with the 300kV system for the northern part of Norway. According to recent improvements in the Norwegian power grid, the northern part has been upgraded to 420kV. Therefore, Rossaga and Trondheim buses were updated to 420 kV and one transmission line was converted to 420kV while the other one was kept as original at 300kV. In addition, the 300kV transmission line from Trondheim to Tretten was converted to 420kV. In addition to the above, a new 420 kV busbar Bergen was added with a new transmission line

from Trondheim to Bergen. All the lines and transformer parameters were adjusted based on the original Nordic 44 network 420kV values.

5.2.2 Addition of Missing HVDC Interconnections

Three new HVDC connections added to the original version of the Nordic 44 model since those were developed recently. Each interconnection was modeled as a load connected to the main bus through a new busbar. The details are shown in Table 5.1.

Table 5.1: New HVDC Connections to Nordic 44 Model

HVDC Link	Connected Main Bus Name & Number	Nord Pool Price Area
Nordbalt	Malmö, 8500	SE4
NordLink	Kristiansand, 5600	NO2
North Sea Link	Kvilldal, 6000	NO2

5.2.3 Addition of Load to Represent DK2

A new load has been added to busbar 8500 Malmö in price area SE4 to represent the power flow between SE4 and DK2. Based on the actual power flow direction, a positive load is used in the PSSE Nordic 44 model to represent power flow from SE4 to DK2, while a negative load is applied to represent flow from DK2 to SE4.

5.2.4 Addition of Wind Power Production

The original version of the Nordic 44 model did not include wind power plants. Therefore, wind power plants were added to the model to match the current Nordic power system production types. In PSSE, the wind machines were modeled as the renewable power plants (wind machine type 4) and dynamic model details are based on the information of DNV. The total installed capacity of each bidding area is distributed among the buses and modeled as a single machine on the respective bus.

5.2.5 Addition of Other Production

In addition to the above mentioned changes, other production was added to the model. Separate machines were added to each country to represent this capacity. This represents the combination of fossil fuel, biomass, waste and solar according to the Svenska kraftnät data.

5.2.6 Details of Total Installed Capacities, Production and Consumption

The Nordic 44 model was updated to reflect the total installed generation capacities for each country. Data for Norway and Finland were sourced from the ENTSO-E Transparency Platform, while data for Sweden were obtained from Statistics Sweden. Two scenarios were developed to simulate the behavior of the Nordic power

system: one representing a summer day and the other a winter day. These scenarios were used to assess the total kinetic energy of the system. Information on power flows between countries and pricing areas, as well as country-level production and consumption and HVDC connection flows for both scenarios, was based on data from the Svenska kraftnät control room. Detailed data on total installed capacities can be found in Appendix A, while Appendix B contains power flow data between countries and pricing areas, and Appendix C includes production and consumption of each country.

After matching the total installed capacities of Norway, Sweden and Finland, actual power flow was matched with each day of the respective scenario. Power consumption of each country was matched with the actual consumption by first scaling and then changing the load of the pricing areas. Actual total power production of each source was matched as well in the model by switching on/off the machines and changing production.

Then checked the total kinetic energy of the two models based on the below equation.

$$E_{k,sys} = \sum_{i=1}^N S_{n,i} H_i \quad (5.1)$$

Here $E_{k,sys}$ is the total kinetic energy of the system, $S_{n,i}$ is MVA base of i^{th} machine and H_i is inertia constant of the i^{th} machine. The calculated figures were adjusted to match the actual kinetic energy range (For the summer day 192.2 - 172.7 GWs and the winter day 249 - 217.8 GWs) of the system.

5.3 Updated PSSE Model Validation

After developing the updated PSSE model, it was necessary to validate it by comparing its performance against actual system behavior. For this, actual measured frequency data for the selected two days (summer day and winter day) with 0.02 second resolution for 1 hour were provided by DNV. The steps followed for the model validation process are discussed below.

Step 1

The actual frequency variation of the Nordic power system from its nominal value was calculated. This was done by determining the difference between the measured frequency at each 0.02 second interval and the nominal value of 50 Hz.

Step 2

Average difference between PSSE simulation and actual frequency Time series actual frequency variation data then converted to the time series load variation based on the frequency factor (MW/Hz). To determine the frequency factor, a load step change was applied during the PSSE dynamic run, and the maximum frequency variation (frequency nadir) was considered for both models (summer day and winter day). The frequency factor was then calculated as follows;

$$\text{Frequency Factor} = \frac{\text{Load Step Change (MW)}}{\text{Maximum Frequency Change (Hz)}}$$

Figure 5.2 illustrates the frequency factor variation for both models under different step load changes.

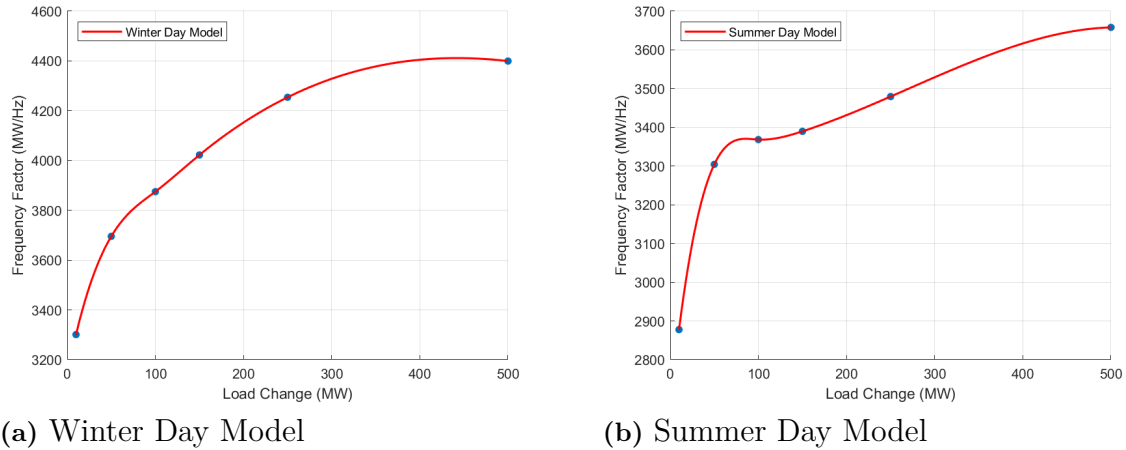


Figure 5.2: Frequency Factor Variation with Load Change

he received actual frequency data corresponds to the normal operating conditions of the system with small load variations. Therefore, the frequency factor related to 100 MW was considered for both cases in this study. The time series load change was then calculated using the following equations.

$$\text{Time Series Load Change (MW)} = \text{Frequency Factor (MW/Hz)} \times \text{Time Series Actual Frequency Variation (Hz)}$$

Figure 5.3 illustrate the load change and frequency variation over a 30 minute period with a 0.5 second resolution on the winter day.

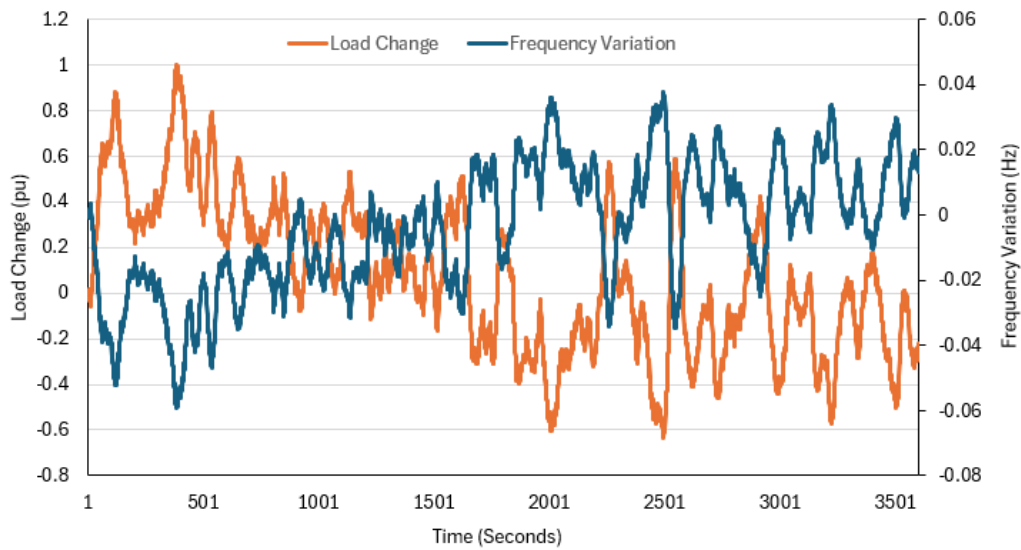


Figure 5.3: Net Load and Frequency Variation for Winter Day

Step 3

The time series load change for a 30 minute period, with a 0.5 second resolution, was averaged across all in service loads in the PSSE model. A dynamic run was then performed using python by applying the time series load variation to all loads, in order to check the PSSE simulation results for system frequency. Additionally, the hydro power droop parameters in the model were adjusted to align with the actual frequency behavior.

Step 4

The PSSE simulation results were compared with the actual frequency data to validate the models for the two scenarios.

Figure 5.4 shows the comparison for the winter day model between the PSSE simulation result at bus number 8500 (Malmö) and the actual recorded frequency data from Bara, Sweden which is located near Malmö.

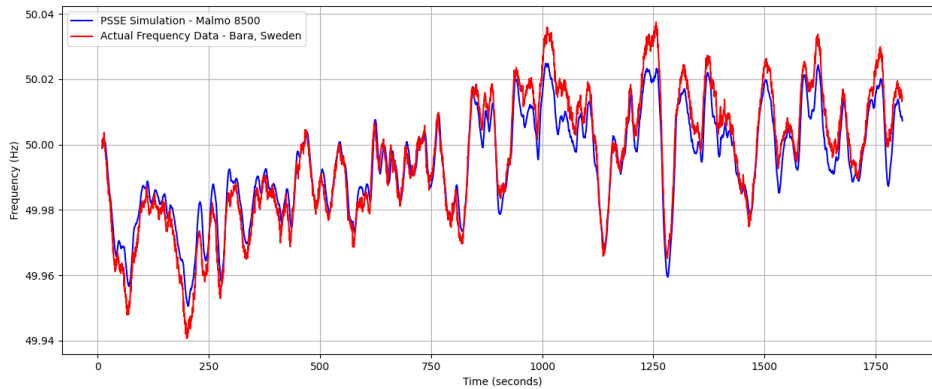


Figure 5.4: Actual frequency variation comparison with PSSE simulation for Winter day - 30min with 0.5sec resolution

Simulation result shows the same frequency variation pattern as the actual frequency by indicating the actual Nordic power system behavior in the simplified PSSE Nordic winter day model. Table 5.2 shows the frequency difference between actual data and simulation in terms of the maximum, minimum and average variation. The average difference is significantly low and therefore this model can be used for the next step of the thesis study.

Table 5.2: Frequency Difference between Actual and Simulation for Winter day

Description	Maximum (Hz)	Minimum (Hz)	Average (Hz)
Difference between actual data and simulation	0.0164	0.0000	0.0047

The comparison for the summer day model is shown in Figure 5.5, presents the simulation result of bus number 8500 (Malmö) and the actual recorded frequency data of Bara, Sweden.

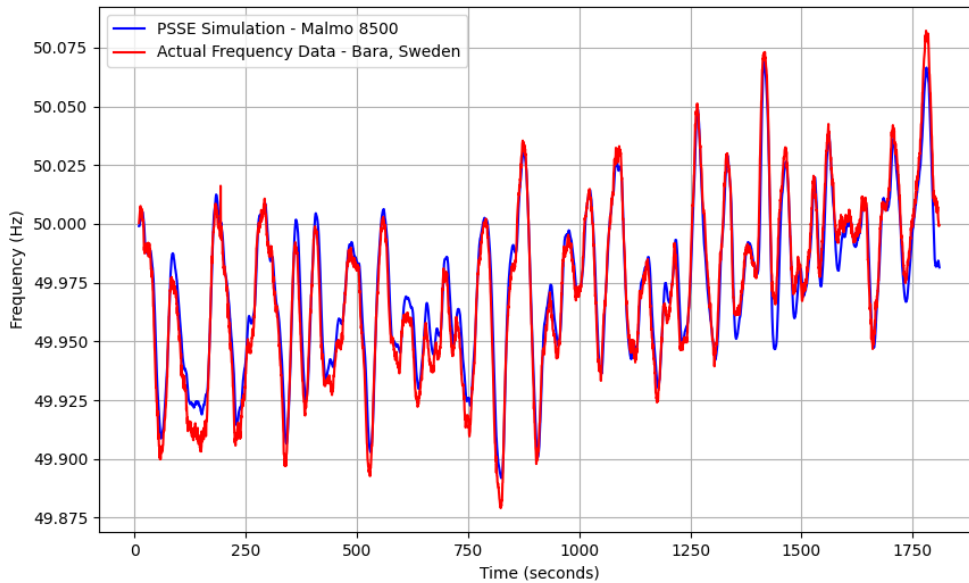


Figure 5.5: Actual frequency variation comparison with PSSE simulation for Summer day - 30min with 0.5sec resolution

This simulation result also shows the same frequency variation pattern as the actual system frequency. Table 5.3 shows the frequency difference between the actual data and simulation in terms of the maximum, minimum and average variation. The average difference is significantly low and therefore this model can be used for the next step of the thesis study.

Table 5.3: Frequency Difference between Actual and Simulation for Summer day

Description	Maximum (Hz)	Minimum (Hz)	Average (Hz)
Difference between actual data and simulation	0.0291	0.0000	0.0066

As discussed above, the updated PSSE models for both the summer and winter day scenarios were successfully validated against actual frequency measurements from the Nordic power system. The simulation results closely matched the actual frequency variation patterns, demonstrating that the simplified models accurately represent the real system behavior. The low average differences between the actual and simulated frequencies confirm the reasonable accuracy of the models. Therefore, these validated models will be used for future scenario development and related simulations in this thesis study.

6

Future Scenarios and Simulation Results

This chapter includes the description of the future scenario development, PSSE simulation results and discussion of the frequency variation of the future Nordic power system.

6.1 Development of Future Scenarios

The development of future scenarios required input from the Nordic TSOs' development plans. Statnett's Long Term Market Analysis 2024-2050 [74], published in February 2025, outlines future development scenarios for Nordic countries covering the period 2024 to 2050. The baseline scenario is mentioned as the most realistic development path of the system from now until 2050. Table 6.1 shows the production and consumption data of Nordic countries for the baseline scenario for the year 2040.

Table 6.1: Production and Consumption of Nordic Countries 2040 [75]

	Norway	Sweden	Finland	Denmark
Hydro (TWh)	145.685	68.855	12.500	-
Onshore Wind (TWh)	22.700	72.000	62.000	16.600
Offshore Wind (TWh)	18.100	17.200	5.000	34.000
Solar (TWh)	8.700	14.300	12.700	13.200
Nuclear (TWh)	-	41.500	29.300	-
Other production (TWh)	1.000	14.413	11.678	11.808
Total Production (TWh)	196.185	228.268	133.178	75.608
Total Consumption (TWh)	194.502	221.629	131.528	68.087

For the development of future PSSE scenarios in this thesis study, the above information has been used as the basis. The method adopted to obtain the power system's production and consumption for the year 2040 in MW is summarized below.

- The country wise growth rates from 2024 to 2040 for each production source and the total consumption were calculated based on the Table 6.1.
- The calculated growth rates for individual power production sources and consumption were then applied to the production and consumption values (in MW) presented in Appendix C for both the summer and winter scenarios.

6. Future Scenarios and Simulation Results

- The summer and winter scenarios presented in Appendix C, do not separately categorize solar production. Therefore, the method described above could not be adopted to calculate the solar capacity contribution for the future PSSE scenarios. The solar MW contribution for the future summer and winter scenario was determined as follows.

$$\text{Solar (MW)} = \text{Total production (MW)} - (\text{Hydro} + \text{Onshore Wind} + \text{Offshore Wind} + \text{Nuclear} + \text{Other}) \text{ (MW)}$$

Predicted total production, individual production by source and total consumption for the year 2040 are summarized in Appendix D. Figure 6.1 illustrates the capacity contribution share of different sources for the present (2024) and future (2040) summer scenarios. Accordingly, a higher capacity contribution to be expected from wind and solar for the future than the present system.

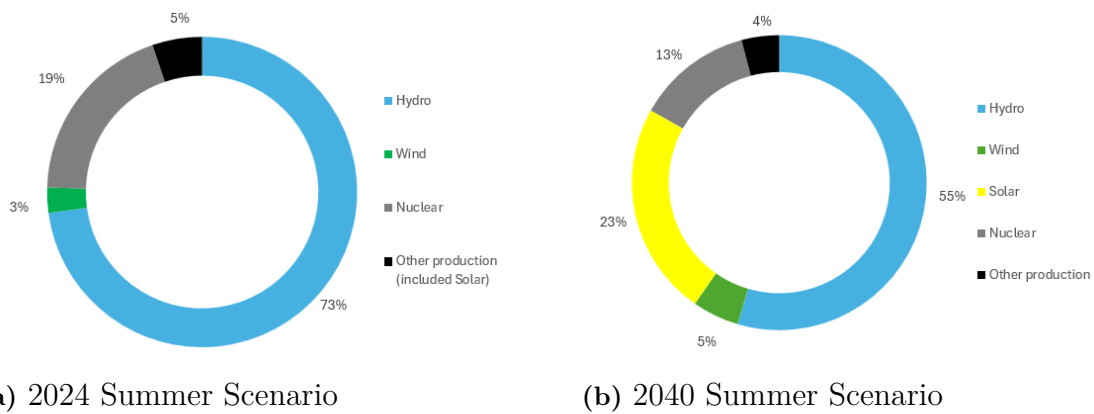


Figure 6.1: Capacity share of Present and Future Summer Scenarios

Figure 6.2 shows the capacity contribution shares for the present (2025) and future (2040) winter scenarios. In this case, a major contribution is expected from wind generation compared to solar.

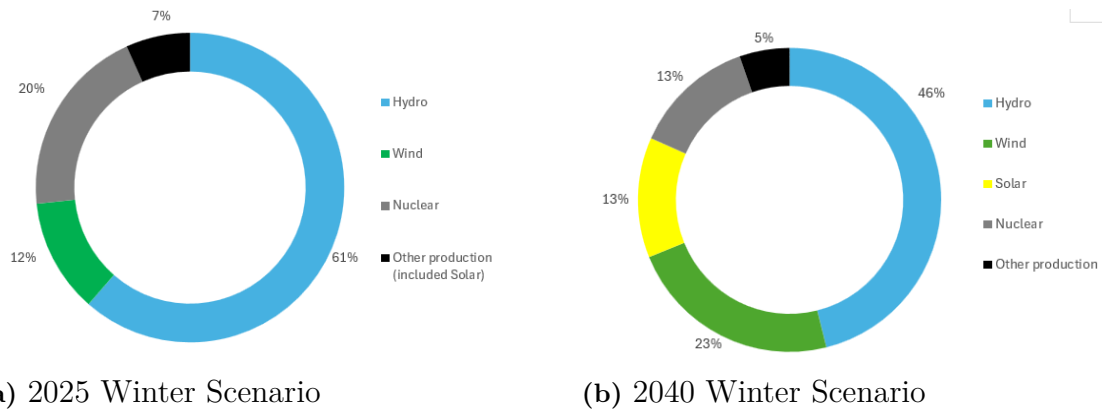


Figure 6.2: Capacity share of Present and Future Winter Scenarios

6.2 PSSE Future Model Development and Simulation

As discussed in Chapter 5, the developed PSSE models for the Summer and Winter scenarios are validated against the present power system. Based on these validated models, two future scenarios for Summer and Winter are developed by applying appropriate scaling.

In both future scenario models, the in-service loads have scaled up with the calculated factor to match with the projected future consumption. The existing machine capacities of hydro, nuclear, wind and other sources have been adjusted according to the production forecasts calculated in Section 6.1. Additionally, the new solar capacities were added for both scenarios.

The time series load variation over a 30 minute period with a 0.5 second resolution mentioned in Chapter 5, was scaled up by a load variation factor (the ratio between the projected consumption and the actual present consumption of the present scenarios) to match the load variation for the projected future consumption. This factor is 1.508 for the winter scenario and 1.507 for the summer scenario. It was then averaged across all in-service loads in the PSSE model. Finally, a dynamic simulation was performed using Python by applying the time series load variation to all loads to assess the PSSE simulation results for the future system frequency.

The assumptions considered for the PSSE modeling and simulation in this thesis study are summarized below.

- Nordic power system is represented by the simplified and updated Nordic 44 model.
- The actual power system operational behavior is represented by the PSSE simulation results of 30 minutes with 0.5 second resolution for present and future scenarios.
- The power production sources for the present and future PSSE models considered only the conventional and renewable energy (wind and solar) sources.
- FCR equipped with the hydro power plants.
- No energy storage technologies and converter control strategies (synthetic inertia) were considered in the future system.
- Total power production, total consumption and power production by source for the 2040 system models are considered as per discussed section 6.1.
- Total system kinetic energy in 2024 winter is 226.16GWs and summer is 189.99GWs. For the 2040 future scenarios kinetic energy in winter is 223.75GWs and summer is 184.56GWs.
- Did not consider the line capacity upgrades, cross-area transfer capacity etc.
- Net export balanced based on the production and consumption of each country for year 2040 system model.

6.2.1 Simulation Results of the Future Winter Day Scenario

Figure 6.3 shows the PSSE simulation result of the future winter day scenario at bus number 8500 (Malmö) compared with the actual frequency and PSSE simulation for the present winter day. This represents the frequency variation of the model over a 30 minute period with 0.5 second resolution.

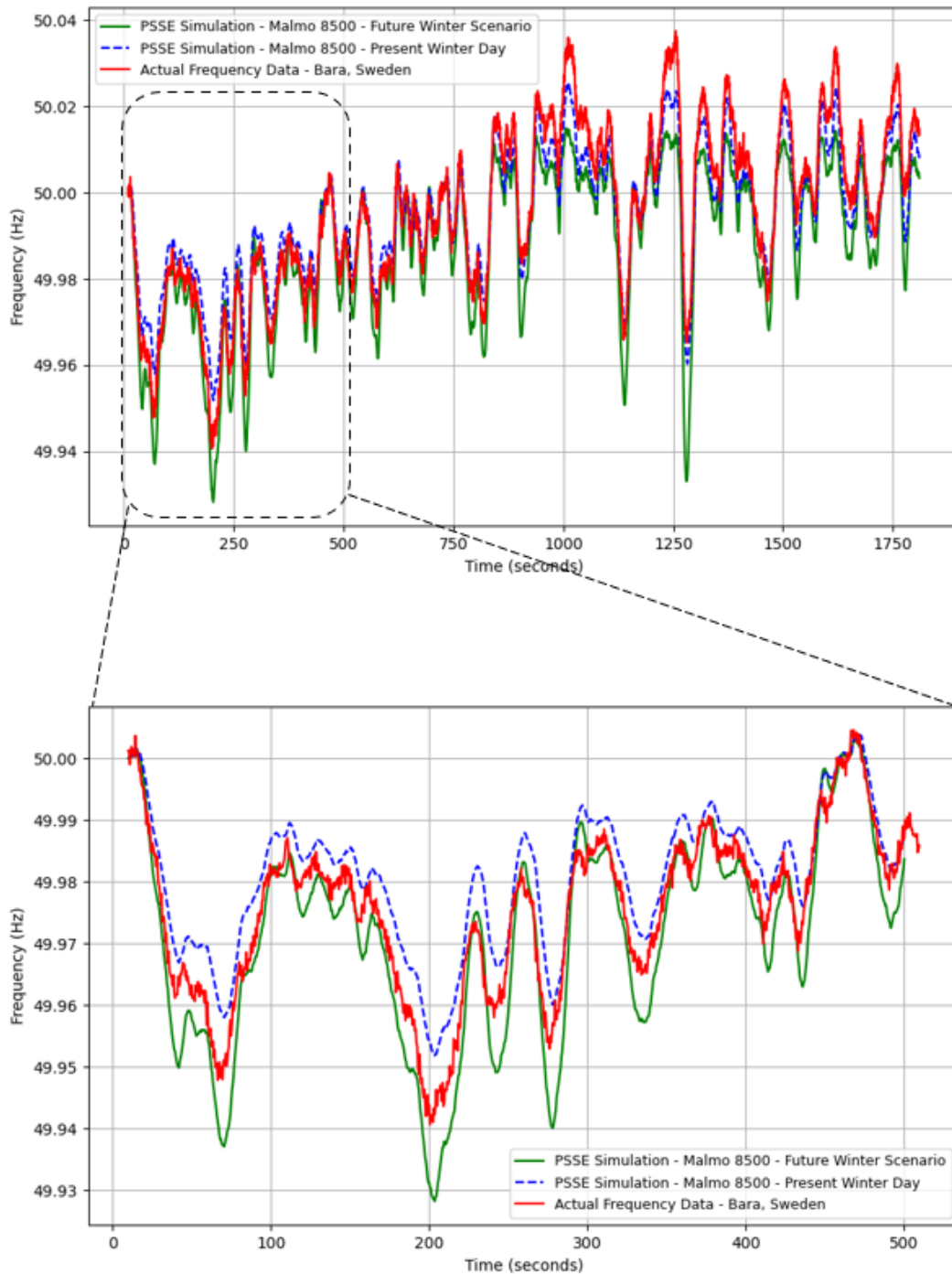


Figure 6.3: PSSE simulation for Future Winter Day Scenario comparison with Actual and PSSE Simulation for Present Winter Day

The simulation results show that the frequency deviation from below 50Hz (under frequency) is higher in future winter scenario while frequency deviation from above 50Hz (over frequency) is considerably low compared to the present system.

Figure 6.4 illustrate the frequency ramp rate variation comparison between present and future scenarios for a one minute with 0.5 sec resolution. Accordingly, the higher ramp rate could be observed in future scenario due to the low system inertia compared to the present system.

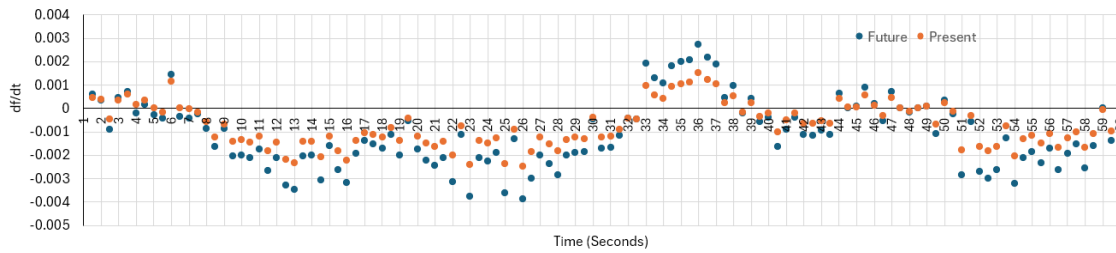


Figure 6.4: Frequency ramp rate comparison between Future Winter Day Scenario and Present Winter Day

Further, an analysis conducted by increasing the load variation of the future winter scenario. This was done by applying higher load variation scale factor to the initial load variation which is 1.508. The frequency deviation for different load variation cases are presented in Figure 6.5.

6. Future Scenarios and Simulation Results

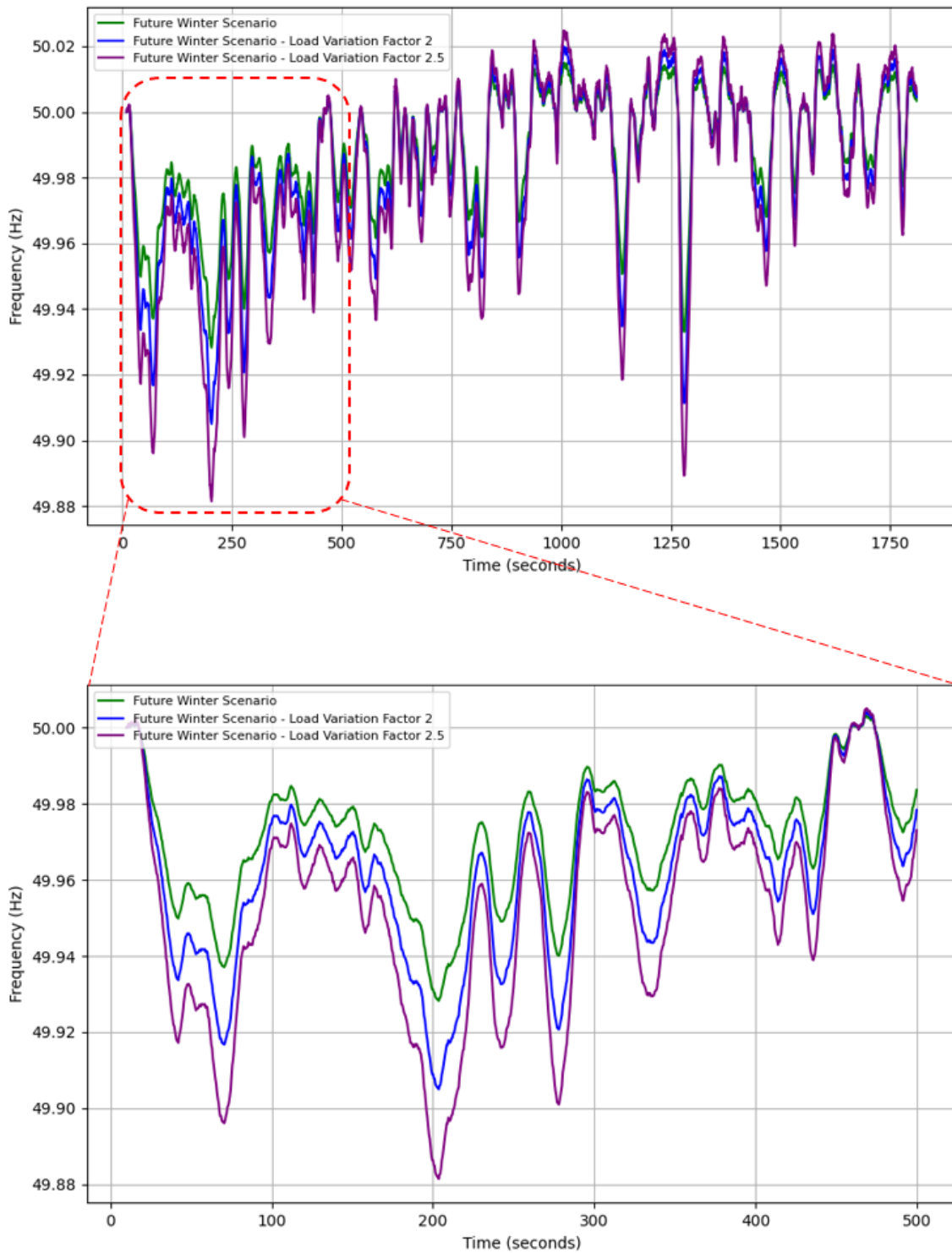


Figure 6.5: Future Winter Scenario with Different Load Variation Scale Factors

Accordingly, it can be seen that the frequency variation becomes higher with the higher load variation of the future system. The resulting frequency deviation of all future cases compared with the present system is presented in Figure 6.6 below. Higher frequency deviation indicates the worsened frequency quality in future, specially moving towards the under frequency situations in normal operation.

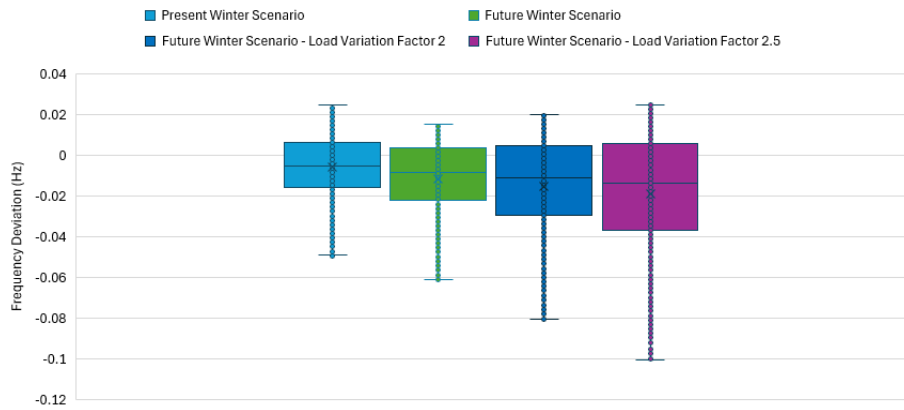


Figure 6.6: Frequency spread comparison with present winter case

6.2.2 Simulation Results of the Future Summer Day Scenario

Figure 6.7 presents the PSSE simulation results for the future summer day scenario at bus 8500 (Malmö), illustrating the frequency variation over a 30 minute period with a 0.5 second resolution. This indicates that the frequency deviations below 50 Hz (under-frequency) are higher in the future summer scenario, while deviations above 50 Hz (over-frequency) are significantly lower compared to the present system.

6. Future Scenarios and Simulation Results

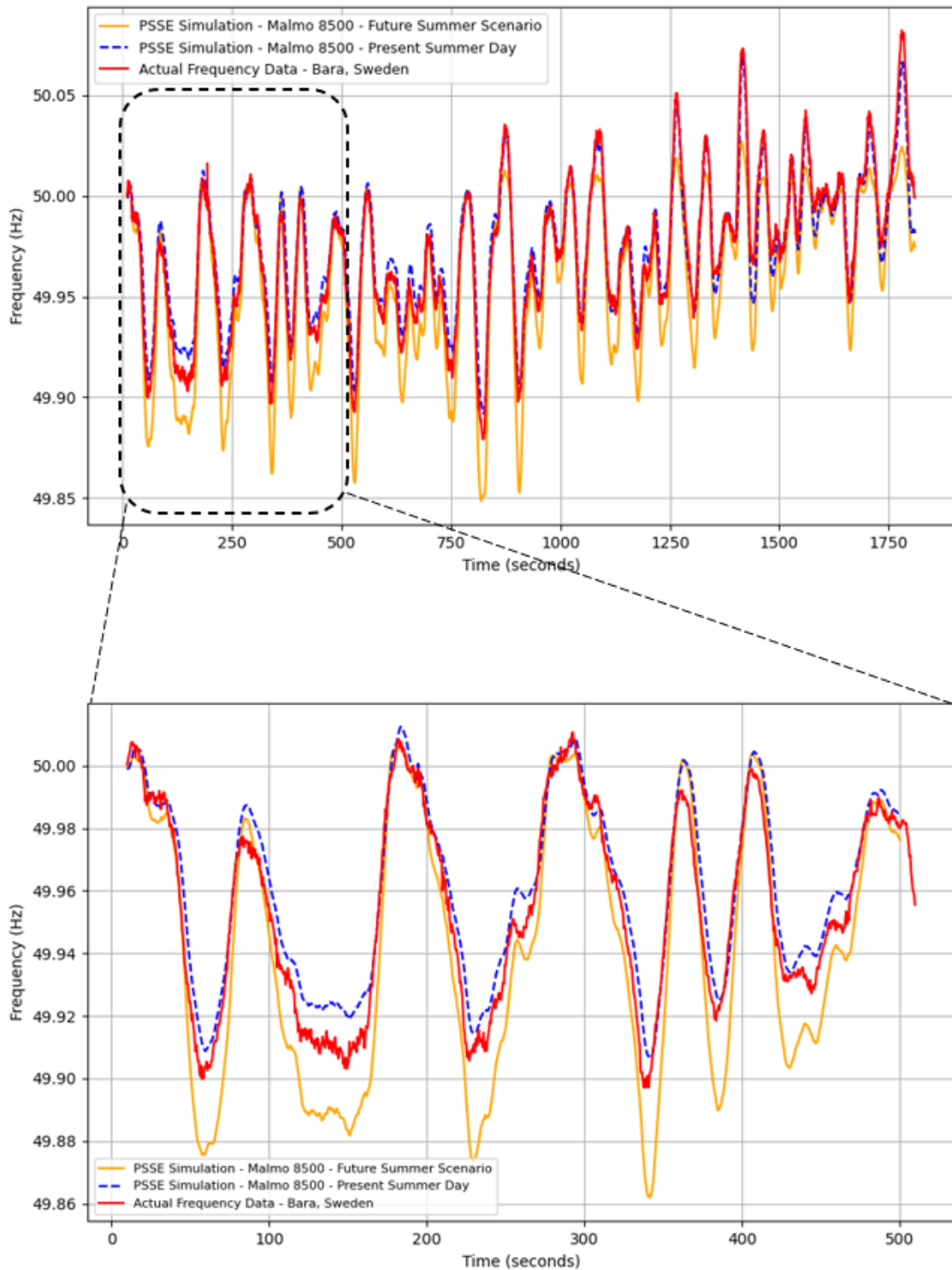


Figure 6.7: PSSE simulation for Future Summer Day Scenario comparison with Actual and PSSE Simulation for Present Summer Day

Figure 6.8 presents the frequency ramp rate comparison between the present and future scenarios over a one minute period with a 0.5 second resolution. A higher ramp rate is observed in the future scenario, related to the lower system inertia

compared to the present system.

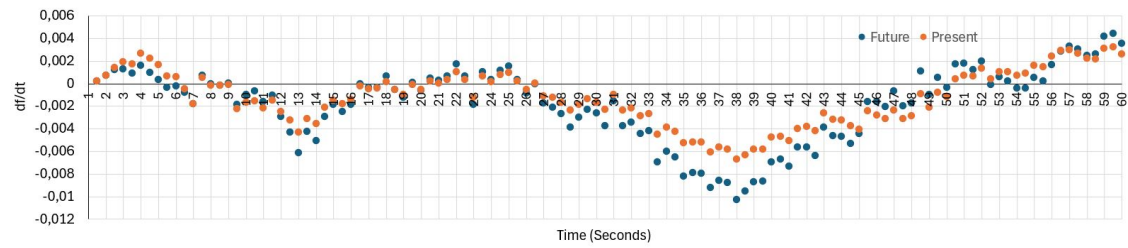


Figure 6.8: Frequency ramp rate comparison between Future Summer Day Scenario and Present Summer Day

In addition, higher load variation scale factors have applied to check the frequency deviation of the model. According to the Figure 6.9, frequency variation is higher when the load variation is increasing.

6. Future Scenarios and Simulation Results

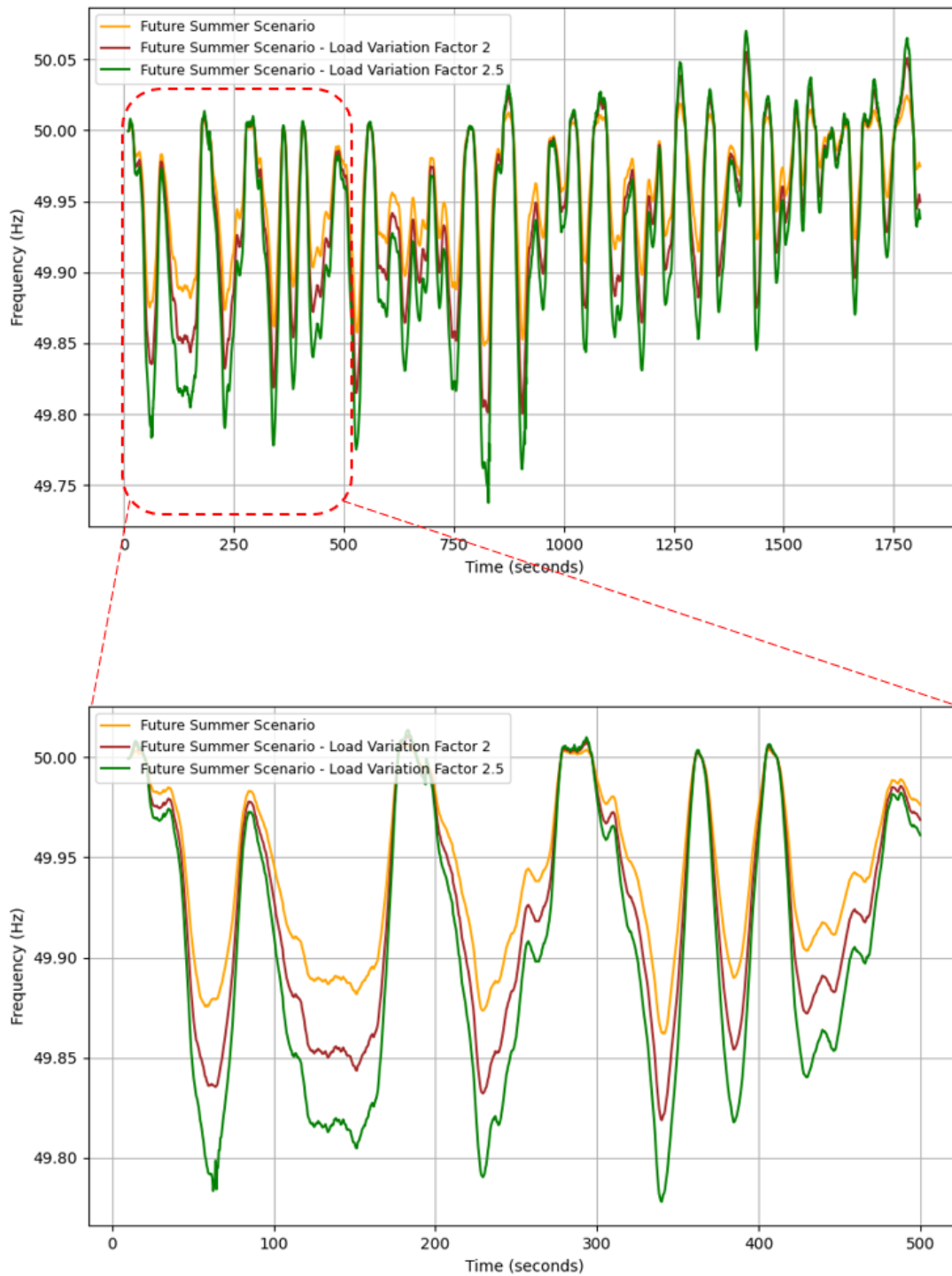


Figure 6.9: Future Summer Scenario with Different Load Variation Scale Factors

Figure 6.10 illustrates the spread of the frequency variation of all the three future cases compared to the present summer day case. Frequency deviation becomes wider in future cases compared to the present summer case indicating higher variability and extreme under frequency values.

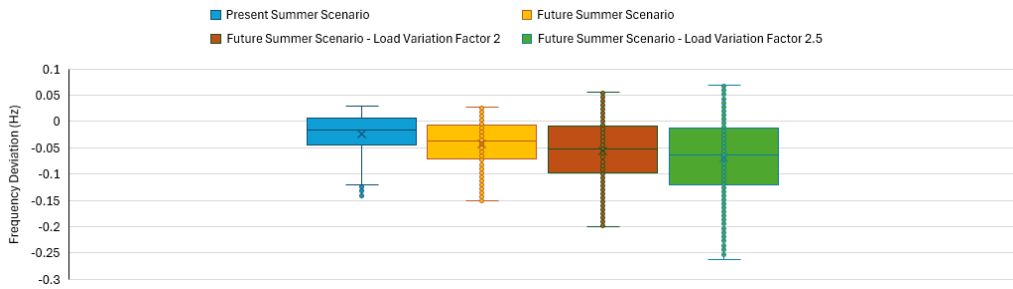


Figure 6.10: Frequency spread comparison with present summer case

6.3 Results Discussion

The PSSE simulation case results presented in subsection 6.2.1 and 6.2.2 will be discussed in this section.

1. According to the Figure 6.3 and Figure 6.7, the two future scenarios (winter and summer) show higher deviations below 50Hz compared to the present system while less deviation above 50Hz. This indicates that the future system with more inverter based production sources compared to the present system can reduce their production quickly to match with the load decrease and will be able to successfully manage the over frequency deviations of the power system under the normal operating conditions. However, the inverter based renewable sources are not able to increase production during the load increase. Therefore, both future scenarios show higher deviation below 50Hz compared to the present system.
2. As per Figure 6.5 and Figure 6.9, an increase in frequency deviation can be observed with higher time series load variation. Both under and over frequency ranges widen as load variation increases, indicating the worsen normal frequency quality of the future power system.
3. In addition to the item 2 above, frequency spread has compared across different load variation cases. As per Figure 6.6, frequency spread widens with higher load variation. Highest frequency deviation below 50Hz is observed in case with load variation factor 2.5. This exceeds the present normal operating range of -0.1Hz for under frequency. However, frequency deviation above 50Hz shows very low values indicating capability of fast system response for load decrease of the future power system. Figure 6.10 for future summer scenarios also show higher frequency variability compared to the present system and the more extreme low value for the load variation factor 2.5 case. Overall, the future system performance shows higher frequency variability than the present system and indicates a trend towards the extreme under frequency levels under normal operating conditions.
4. Figure 6.4 and Figure 6.8 show the frequency ramp rate variation of the fu-

ture winter and summer respectively. Accordingly, higher ramp rates can be observed in the future power system due to the low system inertia compared to the present system.

7

Discussion of Needs, Opportunities and Challenges

This chapter discusses the needs, opportunities, and challenges related to widening the normal frequency band for the Nordic power system, drawing on technological, economic, and regulatory considerations.

There are several studies focused on the requirement of flexible frequency (relaxed normal frequency range) for the power system operation specifically due to the high renewable energy penetration. These sources introduce higher uncertainty and variability to the grid by challenging the power system operation. The study conducted in [76], explore a strategy for the implementation of flexible operational frequency for Korean power system. Further the study outlined the numerous benefits associated with a flexible frequency framework, including cost reduction of frequency ancillary services, efficient utilization of available generation assets and new pricing mechanism. These findings support for the changes in traditional grid operation standards or methods to better align with the evolving energy sector.

7.1 Needs for Widening the Normal Operational Frequency Band

7.1.1 Variable Renewable Energy Integration

The integration of a high share of renewable energy introduces significant variability and unpredictability into the grid. Fluctuations in power output are often more severe and rapid than those of traditional conventional power sources, demanding a more flexible operation to maintain system balance and stability [76]. Expanding the normal operational frequency band allows for greater tolerance of these fluctuations, thereby enhancing the system's flexibility.

7.1.2 Limitations of traditional reserve methods and Constraints on infrastructure expansion

Conventional strategies to control frequency, such as deploying additional fossil fuel based generators for the future are increasingly impractical mainly due to high environmental concerns (e.g., carbon emissions) [76]. Expanding infrastructure to accommodate more reserves (e.g., building new transmission lines or power plants)

is challenging, particularly against fossil fuel based generation. The expansion of the normal operational frequency band will limit these requirements for future power systems.

7.1.3 Improved Utilization of Existing Assets

For a tighter frequency band with the same amount of inertia system, the regulating units need to work harder which comes with the cost of wear and tear. With a relaxed frequency band, existing conventional power plants such as fossil fuel based can operate closer to their rated capacity by improving generation efficiency, optimizing operational cost and deferring the need for new capacity investments. Governor reserves, which typically require units to operate below full load, can be reduced, freeing up more generation for normal operations.

7.1.4 Cost Savings in Frequency Ancillary Services

Expanding the frequency operating range of the grid can substantially lower both the volume and cost of frequency ancillary services. It also allows the power system to withstand greater frequency deviations without requiring immediate corrective action, thereby reducing the dependence on expensive, fast-responding resources. According to a study cited in [76], widening the frequency band in Korea from ± 0.2 Hz to ± 0.5 Hz could lead to a reduction of up to 45% in annual ancillary service costs.

7.2 Opportunities

7.2.1 Differentiated Frequency Quality for Different Components and Loads

According to the discussion in Chapter 5, the required frequency quality for proper functioning of the components is different. The Nordic power system is dominated by large-scale industries which require continuous and fixed operation. These industrial processes as well as medical equipments, data centers etc. require tightly regulated frequency to operate safely and effectively. The widening of the frequency band for the entire grid could lead to malfunctions or reduced performance in such critical applications. Therefore, exact details of these loads and components are required to study the possible tolerances for the entire grid frequency flexibility.

As discussed in [76], by analyzing and customizing the frequency quality requirement and using technologies like BTB (Back-to-Back) VSC HVDC links, the system can selectively supply high quality frequency where needed while operating the main grid within a relaxed frequency range. The advantages of this approach will be the flexibility of frequency control, improved power flow control, and enhanced system stability. The disadvantages will be high capital cost, regulatory and market complexity.

7.2.2 Postponement of Infrastructure Expansion

The widening of the operational frequency band significantly reduces the need for fast response generators or energy storage systems that are typically required to maintain strict frequency regulation. These resources are often expensive to install and operate. By allowing a broader range of acceptable frequency variation, system operators can manage imbalances with less reliance on immediate corrective actions, thereby decreasing the demand for additional infrastructure dedicated to fast frequency control. This operational flexibility can lead to substantial cost savings by delaying or even eliminating the need to invest in new power plants, battery storage facilities, or expanded transmission networks. Furthermore, it eases the financial burden enabling a more economically sustainable approach to grid development. In addition, this strategy also brings environmental benefits by reducing the construction and operation of fossil fuel based peaking plants and battery systems, which are commonly used for fast frequency response. However, during the large disturbances, frequency nadir will reach fast, which will require more fast responding active power support.

7.2.3 Differentiated Electricity Pricing Concept

Widening the normal operational frequency band in the Nordic power system can be implemented through various approaches such as outlined in [76] where consumers are categorized based on their need for frequency quality. Specifically, the system distinguishes between customers who require high frequency quality like sensitive industrial loads and those who can tolerate broader frequency variations. This type of implementation creates an opportunity to introduce a differentiated electricity pricing model, where charges are aligned with the quality of service required. For instance, customers who need high frequency quality would bear additional costs by reflecting the higher expense of maintaining strict frequency control through ancillary services and advanced infrastructure. General consumers who do not rely on such quality could benefit from lower tariffs as they would not be subsidizing services they do not require. This approach promotes both economic fairness and efficient resource allocation within the power system.

7.3 Challenges

7.3.1 Security and Stability Risks During Large Disturbance

The flexible normal frequency band (wider or more relaxed) will cause the lower margin to handle a large disturbance of the system. In power network operation, tighter frequency margins act as a protective buffer by enabling system operators to initiate corrective actions before the frequency reaches the critical limit. However, these safety margins are reduced with a wider frequency range by resulting in the response delay of the system to severe disturbances. This may cause significant frequency deviations during major disturbances by increasing the risk of instability, under-frequency load shedding, or even cascading failures if not properly managed.

Therefore, while a relaxed frequency band improves operational flexibility under normal conditions, it also requires careful planning and enhanced control strategies to ensure resilience and security of the system during extreme events.

7.3.2 Changes in Regulations and Standards

In the Nordic power system, current grid codes and frequency regulations are designed around the synchronized interconnected system with a narrow normal frequency band of 49.90–50.10 Hz. This structure ensures coordinated operation and stability across the Nordic TSOs. However, implementing a wider or more relaxed frequency band would require significant regulatory changes, including updates to national grid codes, operational procedures and market rules. This process will be complex and time-consuming, involving technical, market, legal, and political considerations, as well as alignment with the European regulations established by ENTSO-E.

7.3.3 Technical Upgrades and Investment

Implementing a wider normal frequency band for the Nordic power system may require upgrading grid components, modifying control and protection systems etc. Additionally, frequency monitoring, automation systems, and generator controls may need to be reconfigured or upgraded to operate effectively under the flexible frequency standards. Initial capital investment for these changes can be significant while this can reduce the long-term cost.

8

Conclusions and Future Work

8.1 Conclusions

Due to the projected large scale variable renewable energy addition to the Nordic power system, new requirements must be considered for the future. PSSE results for the future scenario show higher frequency ramp rates and more variability compared to the present power system. Also, the power electronic inverters introduce high-frequency oscillations and resonances across a broader frequency spectrum to the power grid. To achieve accurate frequency measurements and to capture future power system behavior, new frequency measurement methods must be considered due to the drawbacks of the existing methods such as lower sampling rate, delays of the measurements, accuracy etc. The most updated technologies such as Wave Measurement Units based on the point on wave technology will capture the higher variability, fast ramp ups and downs of the frequency, high-frequency oscillations and resonances. Therefore, this method will provide accurate and detailed information of the system for proper monitoring and operation of the future Nordic power system.

Power system components in generation, transmission, distribution and load side have standardized operational limitations for the power system frequency deviation. Most of the components which have rated for 50Hz operation allow $\pm 5\%$ or higher deviation under normal operating conditions while components such as generators, turbines, some medical and industrial equipments have lower margins for the deviations. Therefore, there is a possible margin to allow the normal frequency variation without adversely affecting the impact for the operation and performance of the power system components.

PSSE simulation results for the present winter and summer scenarios are fairly accurate compared with the actual power frequency variation by indicating actual system performance in simplified Nordic 44 model. Future winter and summer scenarios show higher frequency spread, specially towards the under frequency (below 50Hz) compared to the over frequency (above 50Hz) conditions. Due to the high contribution of fast acting inverter based production that can reduce production quickly, the over frequency deviations are handled successfully. However, as inverter based production is not able to increase power output on demand, then under frequency deviations are increasing in future power system model. Therefore, redefinition of the normal frequency bandwidth for the Nordic power system should focus primarily

on the margin below 50 Hz.

Even though there are technical needs and possibilities to change the normal frequency bandwidth, there are several challenges to be considered such as changing the regulations and standards of Nordic synchronized network, collecting detailed information of frequency sensitive components as well as required technical upgrades and investment.

8.2 Future Works

This chapter presents the possible areas for further research related to the frequency measurement and widening the normal frequency bandwidth of the Nordic power system.

- Implementation of laboratory-based test for the different frequency measurement methods and evaluate the accuracy.
- Conduct further analysis of the developed future power system models in this study, focusing the following areas;
 - Changing the variable renewable energy share
 - Adding energy storage technologies and converter control strategies to implement synthetic inertia
- Enhance the PSSE future scenarios with relaxed normal frequency band and explore the system impact/response for the following;
 - Large scale disturbances
 - Maximum reduction of system kinetic energy/inertia without violating system frequency stability
 - Additional MW capacity that can be added to the N-1 contingency limit for a given system kinetic energy level
- This study considered the frequency factor related to the 100 MW load change in PSSE model. This can be further improved by applying different frequency factors in PSSE to match with actual variation.
- Conduct the load change calculation based on the $dP_l = dP_m - 2 \cdot E_k \cdot df/dt$ and check the PSSE simulation result with actual frequency variation.
- Study on flexible frequency operational strategies to achieve the relaxed normal frequency bandwidth for the Nordic power system. For example, more relaxed frequency regulation in the main grid while more sensitive equipment/processes connected separately by ensuring tighten frequency variation.

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A

Appendix - Total Installed Capacities

A.1 Summer Scenario (18-06-2024)

Table A.1: Installed Capacities per Production Type 2024 - Finland and Norway [71]

Type	FI	NO1	NO2	NO3	NO4	NO5
Biomass (MW)	1695	2	0	13	0	0
Fossil Gas (MW)	1742	6	23	0	252	192
Fossil Hard coal (MW)	1410	0	0	0	0	0
Fossil Oil (MW)	1051	0	0	0	0	0
Fossil Peat (MW)	1044	0	0	0	0	0
Hydro Pumped Storage (MW)	0	0	522	60	0	483
Hydro Run-of-river and poundage (MW)	3173	2536	1409	1399	687	844
Hydro Water Reservoir (MW)	0	1420	9816	3416	4907	7102
Nuclear (MW)	4364	0	0	0	0	0
Other (MW)	448	0	0	31	0	0
Other renewable (MW)	392	0	0	22	77	0
Solar (MW)	27	9	0	0	0	0
Waste (MW)	87	32	22	6	0	32
Wind Onshore (MW)	6618	406	1447	2120	1160	0
Total (MW)	22051	4411	13239	7067	7083	8653

Table A.2: Installed Capacity per Production Type 2023 - Sweden [72]

Type	SE1	SE2	SE3	SE4
Hydro (MW)	5357	8083	2652	314
Wind (MW)	3000	6823	3969	2431
Solar (MW)	28	167	2604	1174
Nuclear (MW)	0	0	7001	0
Conventional thermal power (MW)	238	797	4615	2080
Total (MW)	8623	15870	20841	5999

A.2 Winter Scenario (01-02-2025)

Table A.3: Installed Capacities per Production Type 2024 - Finland and Norway [71]

Type	FI	NO1	NO2	NO3	NO4	NO5
Biomass (MW)	1942	2	0	13	0	0
Fossil Gas (MW)	1742	7	23	0	256	192
Fossil Hard coal (MW)	1321	0	0	0	0	0
Fossil Oil (MW)	1051	0	0	0	0	0
Fossil Peat (MW)	850	0	0	0	0	0
Hydro Pumped Storage	0	0	522	60	0	79
Hydro Run-of-river and poundage (MW)	3195	2599	1516	1500	722	892
Hydro Water Reservoir (MW)	0	1402	9871	3422	4914	7104
Nuclear (MW)	4364	0	0	0	0	0
Other (MW)	386	0	0	31	0	0
Other renewable (MW)	362	0	0	22	77	0
Solar (MW)	47	17	0	0	0	0
Waste (MW)	93	32	22	7	0	32
Wind Onshore (MW)	0	0	6	0	0	0
Total (MW)	23577	4465	13407	7175	7129	8299

Table A.4: Installed Capacity per Production Type 2023 - Sweden [72]

Type	SE1	SE2	SE3	SE4
Hydro (MW)	5357	8083	2652	314
Wind (MW)	3000	6823	3969	2431
Solar (MW)	28	167	2604	1174
Nuclear (MW)	0	0	7001	0
Conventional thermal power (MW)	238	797	4615	2080
Total (MW)	8623	15870	20841	5999

B

Appendix - Power Flow

B.1 Summer Day (18-06-2024) and Winter Day Scenario (01-02-2025)

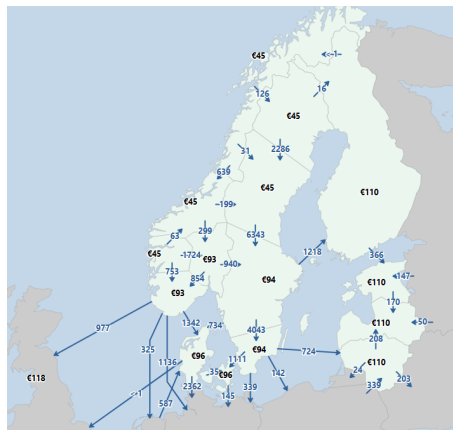


Figure B.1: Power Flow of the Nordic Power System - Summer Day [73]



Figure B.2: Power Flow of the Nordic Power System - Winter Day [73]

C

Appendix - Production and Consumption

C.1 Summer Scenario (18-06-2024)

Table C.1: Actual Production by Source, Total Production and Total Consumption [73]

Type	Finland	Norway	Sweden
Nuclear (MW)	4,571	-	4,571
Hydro (MW)	9,361	18,137	9,361
Wind (MW)	687	111	687
Thermal (MW)	496	165	496
Unspecified (MW)	578	-	578
Total Production (MW)	15,692	18,414	15,692
Total Consumption (MW)	12,646	13,098	12,646

C.2 Winter Scenario (01-02-2025)

Table C.2: Actual Production by Source, Total Production and Total Consumption [73]

Type	Finland	Norway	Sweden
Nuclear (MW)	4,212	-	5,793
Hydro (MW)	1,503	21,011	10,033
Wind (MW)	1,334	1,045	4,055
Thermal (MW)	1,911	150	877
Unspecified (MW)	73	-	629
Total Production (MW)	9,033	22,206	23,928
Total Consumption (MW)	10,199	17,909	17,537

D

Appendix - Future Production and Consumption

D.1 Future Summer Scenario

Table D.1: Predicted Production by Source, Total Production and Total Consumption

Type	Finland	Norway	Sweden
Nuclear (MW)	3,259	-	3,794
Hydro (MW)	2,048	19,009	9,208
Wind (MW)	977	266	1,613
Solar (MW)	4,822	3,524	4,665
Other Production (MW)	935	165	1,191
Total Production (MW)	12,041	22,965	20,470
Total Consumption (MW)	12,597	18,328	20,019

D.2 Future Winter Scenario

Table D.2: Predicted Production by Source, Total Production and Total Consumption

Type	Finland	Norway	Sweden
Nuclear (MW)	4,114	-	5,437
Hydro (MW)	1,352	22,021	10,490
Wind (MW)	4,704	2,508	9,519
Solar (MW)	3,786	3,016	2,594
Other Production (MW)	2,106	150	1,670
Total Production (MW)	16,061	27,695	29,709
Total Consumption (MW)	15,970	25,060	27,762

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