Norwegian University
of Life Sciences

Master's Thesis 2021 30 ECTS
Faculty of Science and Technology
Sonja Monica Berlijn

Forced Oscillation Monitoring and Control in the Nordic Power System
- A NEWEPS Approach

Andreas Svanes
Environmental Physics and Renewable Energy

A common mistake that people make when trying to design something completely foolproof is to underestimate the ingenuity of complete fools.

Douglas Adams
English Author

Acknowledgements

This master thesis marks the completion of my Master's degree in Environmental Science and Renewable Energy at the Norwegian University of Life Sciences (NMBU), and was written during the spring of 2021. I would like to extend a special gratitude to my thesis advisor Sonja Monica Berlijn for great counseling and well informed advice throughout the whole process from origin until finished product. Kjetil Uhlen also deserves thanks for factual guidance with case and theory.

I will be eternally appreciative to Tobias Korten, Krishna Solberg and Ellen Mathiesen for informative and helpful discussions and for making the writing process infinitely more enjoyable and productive. I will also be forever gratefull to all my classmates, friends and family for making the roller-coaster that has been the last five years so rewarding.

The process of writing this thesis has been very educational and has allowed me to explore interesting factors that are essential to build the future power systems. It has given me greater insight into the inner workings of power systems. The thesis is a starting point for further exploration and development of good monitoring and control applications for forced oscillations in the Nordic power grid. It is my hope that Statnett and other stakeholders can find it as a good foundation for further research in this field.

Ås, May, 2021

Andreas
Svanes

Summary

Through the European Green Deal, the European Union is aiming to become the first carbon-neutral continent by 2050. To achieve this goal much of the heavy industry and transportation sector is undergoing electrification or a transition to green hydrogen as the main energy source. This will lead to an increased demand for electricity. Renewable energy sources (RES) are overtaking coal and gas as the main electricity sources in order to decarbonize the production side.

These RESs are much less regulatable than traditional energy sources, which is putting an increased amount of stress on the power grid. The main challenges facing the power systems are decreasing levels of flexibility, inertia, generation and transmission adequacy and frequency quality. For power system operators to better be able to monitor and control the increasingly stressed power system new and superior sensors have to be implemented into the system. One such sensor is a Phasor Measurement Unit (PMU), which can measure voltage and current phasors with a sampling rate of 30-60 measurements per second. PMU data is also time-synchronized to gain a better overview of the system.

A project set up by the Nordic Transmission System Operators (TSOs) to create a joint monitoring and control system is the New Early Warning Early Prevention System (NEWEPS). The NEWEPS project contains nine Work Packages (WP) and this thesis is focusing on WP5, and more specifically on forced oscillations (FOs).

A case study was performed to study the interesting characteristic most FOs have, that their amplitude is largest close to the source. Two scenarios were studied. Scenario 1 performed as expected, but scenario 2 yielded some interesting results. Here the amplitude remained almost the same even far from the source, indicating some possible resonating effects with an electromechanical mode in the system.

Furthermore, a literature search was performed, aimed at researching methods for detecting FOs in a power system and locating their sources. From each search, one method was chosen and studied in detail. They both show great performance on simulated data from the miniWECC model. In addition, the detection algorithm performed very well on real-world historic PMU data and was even able to detect a previously unknown FO.

The author of this master's thesis advises the NEWEPS project to further research their effectiveness in a power system resembling the Nordic power system and to continue the development and integration of these methods.

This thesis studied to what extent FOs can be monitored and controlled in a modern power system. It was found that currently FOs are not monitored during real-time operations in the Nordic system. However, it is the author of this thesis's belief that through the NEWEPS project, the Nordic TSOs will develop well-functioning applications to achieve the goal to monitor and control FOs in real-time using the methods put forth in this thesis.

Sammendrag

Gjennom “the European Green Deal”, tar den europeiske unionen sikte på å bli det første karbon-nøytrale kontinentet innen 2050. For å oppnå dette målet gjennomgår mye av den tunge industrien og transportsektoren en elektrifisering eller overgang til grønt hydrogen som sin primære energikilde. Dette vil føre til en økt etterspørsel etter elektrisitet. Videre må den elektriske produksjonen dekarboniseres. Denne prosessen er godt i gang da fornybare energikilder har overtatt kull og gass som primær kilde til elektrisitet i Europa.

Disse fornybare energikildene er mye mindre regulerbare enn de tradisjonelle energikildene, som setter et større press på kraftnettet. Hovedutfordringene til kraftnettet er synkende nivåer av fleksibilitet, treghet, tilstrekkelighet av generasjon og transmisjon og frekvenskvalitet. For at kraftoperatørene skal kunne mer optimalt observere og kontrollere et kraftsystem under økt stress, så må nye og bedre sensorer bli implementert inn i systemet. En av disse sensorene er en “Phasor Measurement Unit” (PMU). Denne kan måle fasevektoren til strøm og spenning 30-60 ganger i sekundet, hvor disse målingene også er tidssynkronisert for å få en bedre oversikt over nettet.

Et prosjekt startet av de nordiske systemoperatørene for å lage et felles overvåknings- og kontrollsystem er “New Early Warning Early Prevention System’ (NEWEPS). NEWEPS-prosjektet består av ni arbeidspakker (WP), og denne master oppgaven fokuserer på WP5 nærmere bestemt på tvungne svingninger.

En casestudie ble utført for å studere en interessant egenskap de fleste tvungne svingninger har, nemelig at amplituden deres er størst nær kilden til svingningen. To scenarier ble studert. Scenario 1 ga forventede resultater, mens scenario 2 ga uforutsette resultater. Her forble amplituden nesten like stor, selv langt fra kilden, noe som indikerer mulige resonanseffekter mellom den tvungne svingningen og en elektromekanisk svingning i systemet.

Videre ble det utført et litteratursøk, rettet mot å undersøke ulike metoder for å oppdage tvungne svingninger i et kraftsystem og lokalisere kildene. Fra hver kategori ble en metode valgt og studert i detalj. Begge de studerte metodene viser god ytelse på

simulerte data fra miniWECC-modellen. I tillegg fungerte deteksjonsalgoritmen veldig godt på historiske PMU-data, hvor den også klarte å oppdage en tidligere ukjent tvungen svingning. Forfatteren av denne masteroppgaven anbefaler NEWEPS-prosjektet å undersøke effektiviteten til metodene i et kraftsystem som ligner det nordiske kraftsystemet og fortsette utviklingen og integreringen av disse metodene.

Denne oppgaven har studert i hvilken grad tvungne svingninger kan overvåkes og kontrolleres i et moderne kraftsystem. Foreløpig blir ikke tvungne svingninger overvåket under sanntidsoperasjon i det nordiske systemet. Forfatteren av denne oppgaven tror derimot at de nordiske systemoperatørene kan utvikle velfungerende applikasjoner, for å oppnå målet om å overvåke og kontrollere tvungne svingninger i sanntid. Dette vil bli gjort i NEWEPS prosjektet ved hjelp av metodene denne oppgaven har presentert.

Table of Contents

Acknowledgements ii
Summary iii
Sammendrag v
Table of Contents vii
List of Figures ix
List of Abbreviations x

1 Introduction **1**
1.1 Background and Motivation 1
1.2 Scope and Limitations 2
1.3 Research Question 2

2 Challenges in the Nordic Synchronous Area **4**
2.1 The European Green Deal 4
2.2 Ten Year Network Development Plan 5
2.3 The Nordic Power System 6
2.4 Challenges (and Opportunities) 6
2.4.1 Flexibility 8
2.4.2 Inertia 9
2.4.3 Generation and Transmission Adequacy 10
2.4.4 Frequency Quality 11
2.5 RDI Roadmap 11

3 NEWEPS, PMU & SCADA **14**
3.1 NEWEPS 14
3.2 PMU and SCADA 15
3.2.1 Synchrophasors 15
3.2.2 SCADA 16
3.2.3 PMU 17
3.2.4 SCADA with PMU 17

4 Methodology 19
4.1 Literature Studies 19
4.2 Technology Readiness Level 20
4.3 Case Study 20

5 Power System Stability and Oscillation Theory 23
5.1 Power System Stability 23
5.2 Transient Stability 25
5.3 Types of Oscillations 30
5.3.1 Ambient Responses 31
5.3.2 Transient Responses 31
5.3.3 Forced Responses 32

6 Case study 35
6.1 Creating a Forced Oscillation 35
6.2 Results Case Study 36

7 Results from Literature Search 38
7.1 Detecting Forced Oscillations 38
7.2 Locating the Source of Forced Oscillations 41

8 Discussion 46
8.1 Literature Selection and PMUs 46
8.2 Case Study Discussion 47
8.3 Detection Algorithm 47
8.4 Localization Method 49

9 Conclusion and Future Work 51
9.1 Conclusions 51
9.2 Future Work 52

References 54

Appendix A TRLs Explained. 57

List of Figures

2.1 Main routes to decarbonization. 5
2.2 Power flow in the Nordic power system. 7
2.3 Expected Nordic power consumption. 8
2.4 Available inertia and flexibility. 9
2.5 Generation and transmission capacity, and frequency quality. 10
2.6 ENTSO-E roadmap clusters. 12
2.7 Milestones in flagship 6. 13

3.1 Conceptual overview of NEWEPS. 15
3.2 Voltage signal and accompanying phasor diagram. 16
3.3 PMU vs SCADA sample rates. 18

4.1 TRL overview. 20
4.2 Map of the Norwegian power grid. 21

5.1 The different types of power system stabilities. 24
5.2 Transient stability illustration. 25
5.3 Synchronous generator connected to grid. 27
5.4 Plot of power vs power angle (1). 28
5.5 Illustration of critical clearing angle. 29
5.6 Simple PSD graph. 32
5.7 Typical frequency vs time graph. 33

6.1 Case graph 1. 36
6.2 Case graph 2. 37

7.1 Practical overview of setup in the localization method. 43

List of Abbreviations

DFT	Discrete Fourier Transformation
DSO	Distribution System Operator
EGD	European Green Deal
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FO	Forced Oscillation
GPS	Global Positioning System
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
MTU	Master Terminal Unit
NEWEPS	New Early Warning Early Prevention System
NMBU	Norwegian University of Life Sciences
p.u.	per-unit
P2X	Power 2 X
PLC	Programmable Logic Controllers
PMU	Phasor Measurement Unit
PSD	Power Spectral Density
PSS/E	Power System Simulator for Engineering
RDI	Research, Development and Innovation
RES	Renewable Energy Sources
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SE	State Estimator
SNR	Signal-to-Noise Ratio

TRL	Technology Readiness Level
TSO	Transmission System Operators
TYNDP	Ten Year Network Development Plan
UK	United Kingdom
WAM	Wide Area Monitoring
wNAPS	western North American Power System
WP	Work Package

1. Introduction

1.1 Background and Motivation

Renewable energy sources (RES) are contributing to a less stable power grid [1]. Yet they are essential to the future of our power systems. In a world that is getting more and more digitalized and where electricity is becoming increasingly important, it is paramount to ensure that the produced electricity is carbon-neutral [2]. Previously Europe's electricity mix has been dominated by non-renewable energy sources such as coal and gas. But in 2020 RES overtook the role of fossil fuels and became the main source of electricity in Europe [3]. The share of RES in the electricity mix is expected to continue increasing as the European Union (EU) in 2019 implemented the European Green Deal (EGD), which sets out to make Europe the first carbon-neutral continent by 2050 [4].

To meet the increased production and provide enough electricity, a stronger and more reliable power grid is needed. However, with the increasing need for electricity and increased share of RES providing this electricity, the grid is becoming more unstable. Flexibility, stability and adequacy are challenges the future power system will face because renewable energy sources are less regulatable and can not provide the same level of inertia as traditional power plants. In addition, new consumers such as electric vehicles and data-centers are affecting the power consumption of the power system balance.

With less regulatable power consumption and generation, new sensors are needed to ensure system operators can respond to disturbances quicker than before. One type of sensor that is being widely implemented around the world is the Phasor Measurement Unit (PMU) because it can provide time-synchronized measurements with very high resolution [5], [6].

Oscillations are system responses to disturbances that require high resolution to visualize properly. These oscillations can make the system highly unstable and in many cases damage equipment or highly sensitive loads. Oscillations can be split into two categories, natural and forced. Natural oscillations get their characteristics from the system itself, while forced oscillations (FOs) are characterized by the driving input which is creating the oscillations [7]. The sources of FOs and how to deal with them is an area that has not received widespread interest until recently and hence much research is still needed on the subject.

New Early Warning Early Prevention System (NEWEPS) is a project started in 2019 as a collaboration between the transmission system operators (TSOs) of Norway, Denmark, Sweden and Finland. In addition, some of the Nordic research institutes and universities are involved [8]. The focus is to develop a joint Nordic information system with new control and monitoring applications such that the future stability of the Nordic power grid is secured.

1.2 Scope and Limitations

The NEWEPS project is divided into nine Work Packages (WP) each with its focus area, and for this thesis, the main focus will be on WP5 ("Oscillation monitoring assessment"). More specifically FOs will be at the center of attention. The thesis will bring to light methods for detecting and dealing with FOs that show great preliminary results in the literature.

Furthermore, a case study that aimed at confirming some forced oscillation theory was performed by the author. The case data is provided by Statnett SF. The NEWEPS project deals with the whole Nordic region, however, the data is specific to a portion of the Norwegian power grid, further narrowing the span of this thesis. In general, the challenges faced by the Nordic countries are very similar and hence conclusions made in this thesis can be generalized to regard the whole of the Nordic region.

A master thesis at the Norwegian University of Life Sciences (NMBU) only lasts just over four months and hence certain decisions had to be made limiting the size of the case study and literature review. A comprehensive overview of the literature will be provided. Articles that provide simulations or testing of their method will be chosen to get a grasp of their reliability. Further testing of these methods on a test system simulating the Nordic power system will be an area for future work done by Ph.D. students or other researchers.

1.3 Research Question

The backbone of this thesis will be to investigate current research made on the field of FOs in power systems. Based on this, as well as the scope and limitations presented above this thesis sets out to explore the following research question:

> "To what extent can Forced Oscillations be monitored and controlled in a modern power system, using PMUs?"

In the process of answering this question these further topics will be studied:

- ”How are forced oscillations formed and what are some of the effects they have in the power system?”
- ”Which methods are currently available and are being researched regarding the detection of forced oscillations?”
- ”Which methods are available that can locate the source of forced oscillations in the power system?”

2. Challenges in the Nordic Synchronous Area

2.1 The European Green Deal

The European Green Deal (EGD) has the aim to make Europe the first climate-neutral continent by 2050 and is a growth strategy and a response from the European Union (EU) to several of the climate and environmental challenges facing the world today. Such challenges are the pollution and destruction of the oceans and forests, a huge decrease in the biodiversity as 1 million species are about to die out and the atmosphere is heating up. The deal will transform the EU into a society with economic growth that is decoupled from the usage of resources and zero net emissions of greenhouse gasses by the year 2050 [4].

As part of achieving zero net emissions by 2050, the EGD aims to cut greenhouse gas emissions so that in 2030 it will be 50% less compared to the level that was recorded in 1990 [4]. To achieve this three main routes should be taken; improving the energy efficiency, reducing the demand for carbon-intensive products and services, and deploy decarbonization technologies across all sectors as can be seen in Figure 2.1 [2].

As it is displayed in Figure 2.1 there will be a power demand increase by a factor of 4-6 as a result of the electrification. It is also shown that there is an increase in demand for hydrogen (Power 2 X), which leads to a great increase in electricity consumption from this sector, shown in Figure 2.3. The case for increasing P2X, especially for green hydrogen, is that it can become a source of flexibility in the power grid [9]. As will be discussed later there will be an increased demand for flexibility in the power grid with an increased share of renewable energy sources connected to the grid. It can be seen in Figure 2.1 that both heavy industry and heavy-duty transport are areas where reducing the demand for carbon-intensive products is of large interest. In many cases, this will be done through electrification which in turn will increase the need for electricity [2].

The production of electricity will have to follow the increased demand for it, and if the EU

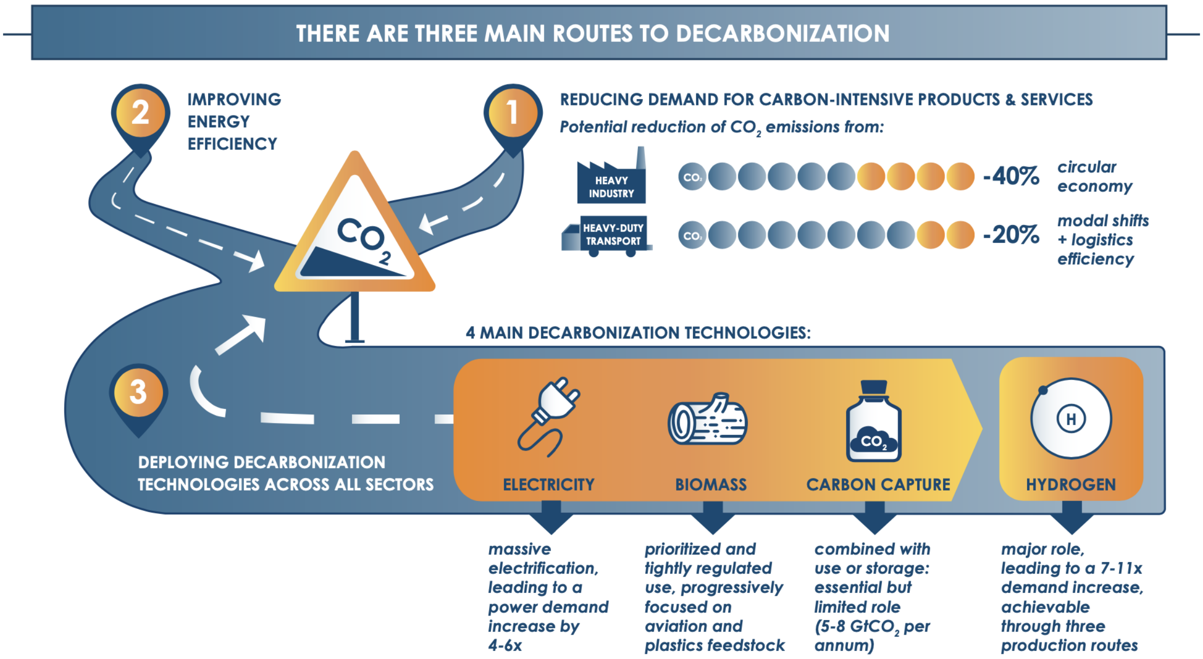

Figure 2.1: Illustration showing the three main routes to decarbonization. This thesis will focus on route 3 and specifically electrification and hydrogen (Power2X) [2].

wants to meet its target of zero net carbon emissions by 2050 all of this new production has to come from renewable resources like wind and solar power. In addition to building wind and solar power for the new electricity demanded, there are plans to phase out much of the current thermal power plants running on coal and other non-renewable resources, which then need to be replaced with renewable energy. Although the increased share of renewable energy in the energy production mix is good from an environmental perspective, it can also bring along new challenges that need to be addressed. Two central problems that can arise are that there will be less flexibility in the power system and there will be a need to upgrade the current transmission lines. But there are also a lot of other problems that can arise which will be discussed further in the following sections.

2.2 Ten Year Network Development Plan

The TYNDP is a pan-European plan for electricity infrastructure development created by the European Network of Transmission System Operators for Electricity (ENTSO-E). The report for 2020 investigates different scenarios and projects that are planned for the nearest future [10]. It is stated that the transmission system will be the backbone of the decarbonized energy system as electrification will be the effective way of reaching the targets set for decarbonization. TYNDP proposes 154 transmission projects and 26 electricity storage projects, which it recognizes as important for the future energy system [11]. Co-operation between nations is seen as one of the most important strategies for a stable future and cross-border transmission lines will hence be very important. There are plans in place for a 93 GW increase in the cross-border capacity by 2040 [11]. Two of these projects plan to connect Norway with United Kingdom (UK) and Germany through the North Sea Link and NordLink respectively. This will then connect the Nordic synchronous area with central Europe and UK, which will have certain consequences and benefits for the Nordic power grid.

2.3 The Nordic Power System

The Nordic power system is a synchronous area with a common frequency (50 Hz) and power flowing between regions inside the country and across country borders [12]. It is a collaboration between the power systems in Norway, Sweden, Denmark and Finland, and their respective TSO's; Statnett, Svenska kraftnät, Energinet.dk and Fingrid. Each country is divided into different price regions to prevent bottlenecks in the system by encouraging a balance between production and consumption in each region. In Figure 2.2 the power-flow in the Nordic power system on a given date is depicted [13]. As can be seen in the bottom part of the figure, there is also some power flow from the Nordic system to central Europe connecting these different synchronous areas. All the TSO's have to work together to ensure a stable frequency at all times when the power flows across price regions and country borders [12].

As previously stated one challenge for the future is going to be the increased demand for electricity. At a webinar in 2021 Statnett, Svenska kraftnät, Energinet.dk and Fingrid presented some numbers on the expected Nordic consumption in 2020, 2030 and 2040, all presented in Figure 2.3. Generation of green hydrogen or P2X stands for the highest increase in demand, while electrification of industry and transportation also contributes a lot to the expected 260 TWh increase in electricity consumption in the Nordic countries [14]. The presenters said the numbers are subject to changes, but the general trend should still be true. This further highlights the need for more renewable energy sources to meet demand and the possible challenges and opportunities this will bring to the power grid operations.

2.4 Challenges (and Opportunities)

In 2016 the 4 Nordic TSOs published a report about the coming challenges and opportunities in the Nordic power system up until 2025. The main drivers for the challenges are much the same as for the European system as a whole, namely an increased percentage of renewable energy in the energy production mix as well as increased electrification and demand for electricity in new loads and changing industries [12]. The problem with

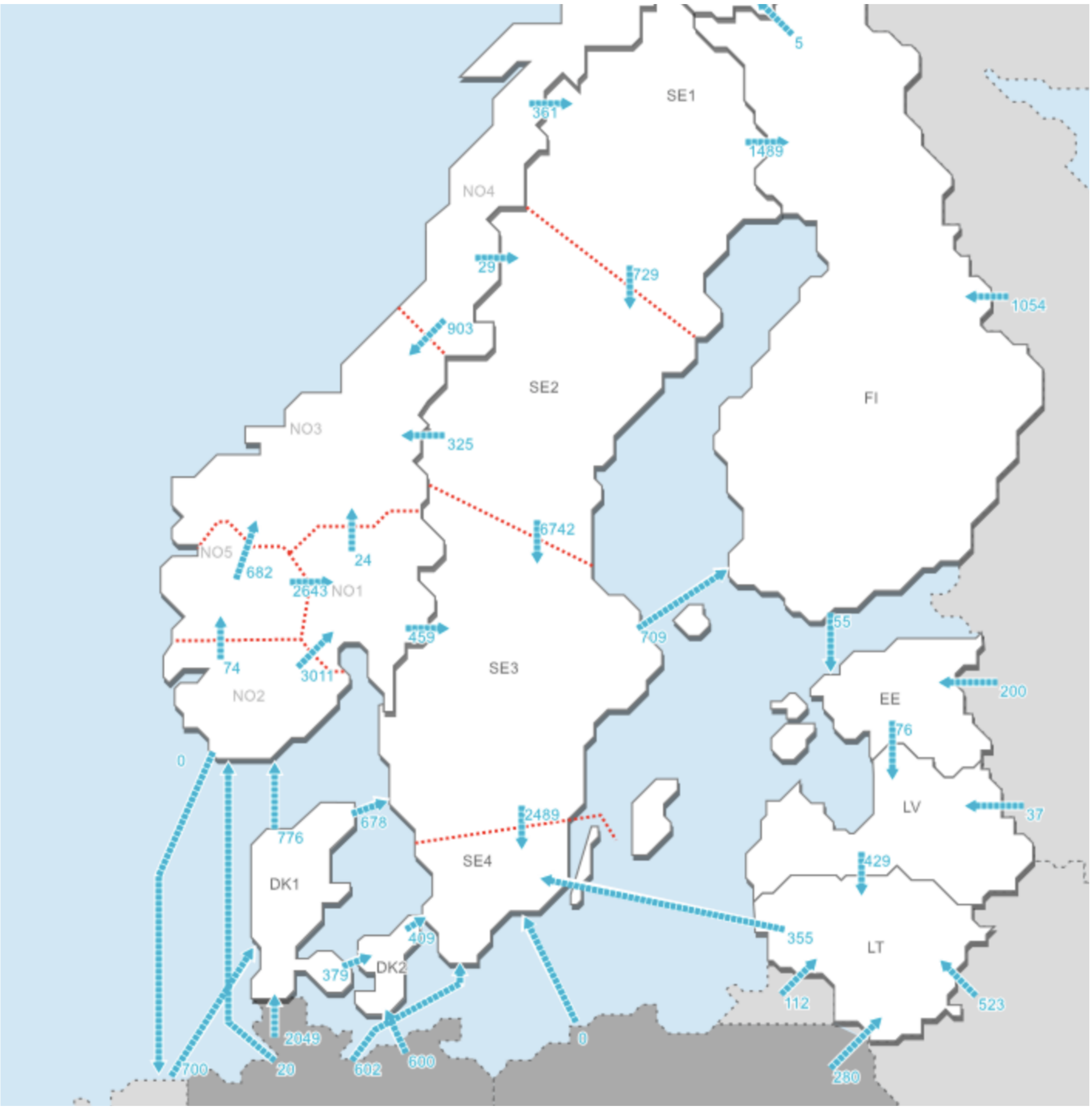

Figure 2.2: Illustration showing the power flow (in MW) in the Nordic Power system on the 12. February 2021. The Baltic countries are also highlighted although they are not part of the Nordic system. The illustration is gathered from Statnett.no [13]

renewable resources like wind and solar power is that they are non-regulatable. This creates problems for the operators in the control rooms of the TSOs because it will be harder to keep production and consumption on the same level. In the report, the main challenges foreseen are: meeting the demand for flexibility, maintaining a good frequency quality and high enough inertia in the system as well as having an adequate generation and transmission capacity [12].

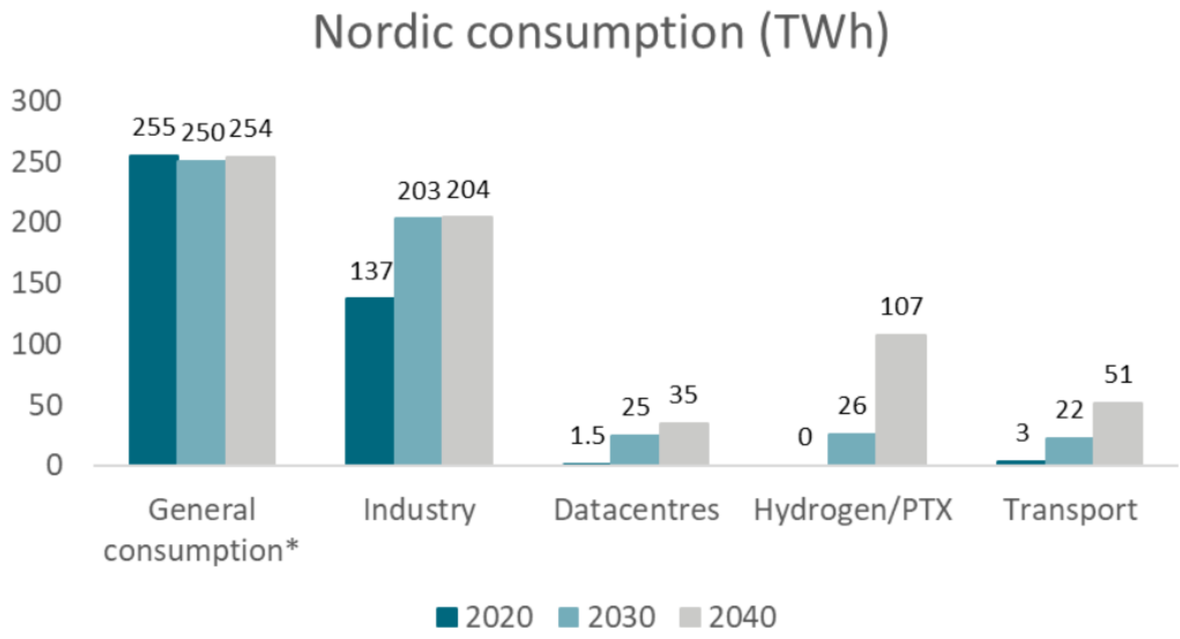

Figure 2.3: The expected levels of electricity consumption for different sectors in 2020, 2030 and 2040. General consumption is not expected to increase, while Power2X will stand for the highest increase. The numbers are subject to change, but the general trend is expected to stay the same [14]

2.4.1 Flexibility

In the power grid flexibility describes how well consumption and production can be controlled. The levels of output and input must be changed to make them as close to equal as possible in both the short and long term. Therefore, having significant flexibility in the system is very important. Flexibility can as stated come from having the possibility to change the levels of production and consumption, but it can also come from using different forms of energy storage to store overproduction or contribute to underproduction when necessary [12]. With an increased share of irregular renewable energy the need for flexibility (in the form of storage) in the system increases, which is expected to happen from 2015 to 2025 (Figure 2.4.b). In periods with low consumption the hydro-power and thermal power plants, which usually provide lots of flexibility and inertia to the system, will usually be turned down/off to keep production and consumption equal. When this is the case the possibility to rapidly change the production to meet demand will be lower and by definition, the flexibility is lower. Some identified solutions are to integrate batteries (or other storage forms) and make the renewable resources run at lower than max so they can be up-regulated if needed [12].

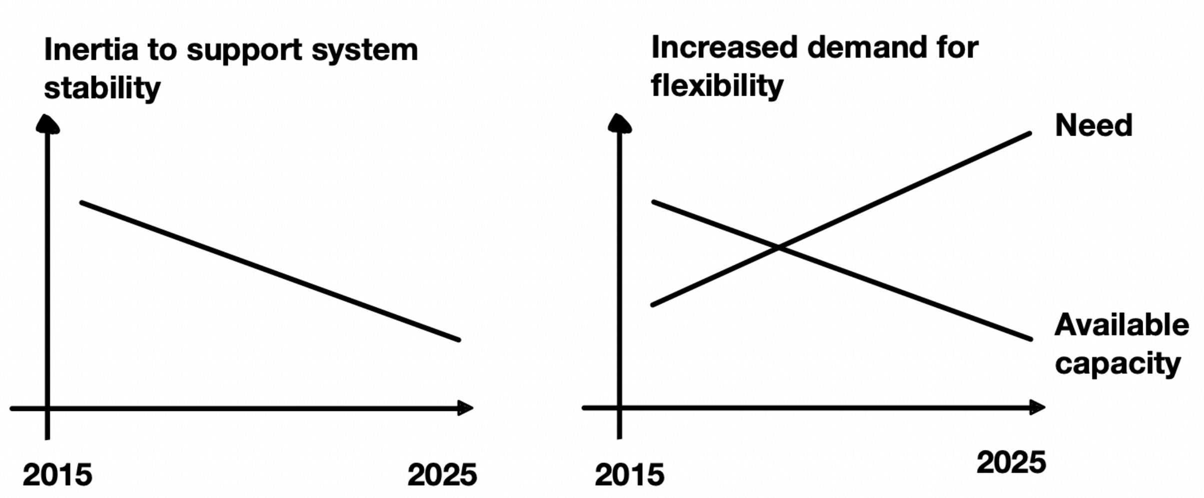

Figure 2.4: **a**: The expected trend in available inertia in the Nordic power system up to 2025. **b**: Expected available flexibility and needed flexibility in the power system until 2025. Inspiration to graphs gathered from lecture by Sonja M. Berlijn [15].

2.4.2 Inertia

Flexibility is very connected to inertia, which is the resistance a physical object has to a change in its motion. In traditional power systems, large synchronous generators rotate with a speed equal to the frequency of the system, and the inertia of the system is the resistance to changes in this frequency when the balance between production and generation changes. If one generator in the system is disconnected, the rotational kinetic energy of the other generators keeps the generation level for a short while until operators can up the production to regain the balance at 50 Hz. If inertia gets too low the frequency will drop too rapidly so operators can't react quickly enough and the chances for blackouts are severe. Wind turbines and solar panels do not have these huge rotating masses, which means they do not contain the same inertia. The introduction of more renewable energy and out-facing of thermal plants will reduce the amount of inertia available (Figure 2.4.a). Therefore the inertia lost must be replaced to secure good system operations. In addition to this, the introduction of more loads into the synchronous area increases the amount of inertia demanded [12]. Calculations can be done to find a minimum amount of kinetic energy (a way to measure inertia) that should be present in the system. In the report, it was expected that in 2025 the Nordic power system will have kinetic energy below this minimum level (120-145 GW) between 1 and 19% of the time [12]. Some solutions to counteract low inertia are to introduce synthetic inertia in the form of battery systems or high voltage direct current (HVDC) links to outside the synchronous area, but also to get more flexibility in the system. It is then important that this inertia behaves similarly to traditional synchronous machines when there is a frequency variation. Other options can be to install rotating masses or system protection schemes, which for example disconnect loads when needed [12].

2.4.3 Generation and Transmission Adequacy

Both generation and transmission adequacy is strongly connected to the security of supply. Generation is connected by providing the available production to meet the demand at all times. Having adequate transmission capacity can provide good security of supply because if the power balance is locally unbalanced, power can be imported/exported from or to another region. If transmission capacity were under par then this scenario could create bottlenecks or generally not be able to deliver the required power, which in turn could affect the frequency and stability of the whole power system (as it is all a large synchronous area) [12]. As can be seen in Figure 2.5.a both generation and transmission capacity will decrease in the following years. Generation adequacy is challenged with the need for more production due to the large electrification of society. This leads to less predictability in how much power will be produced in the coming hours or days and building reserves is therefore becoming increasingly important to uphold the security of supply. A solution presented in the report for both challenges is an increased focus on building good models for the future power system. This will give information about the state of the adequacy in the future and hence guide which areas to invest in. There is also a large focus on collaboration, not only in the Nordic region but also between the Nordic countries and the Baltic region and Europe. Here there is a focus on agreeing on certain standards for the level of adequacy in generation and increased investment on transmission across land borders (as previously stated in the TYNDP) [12].

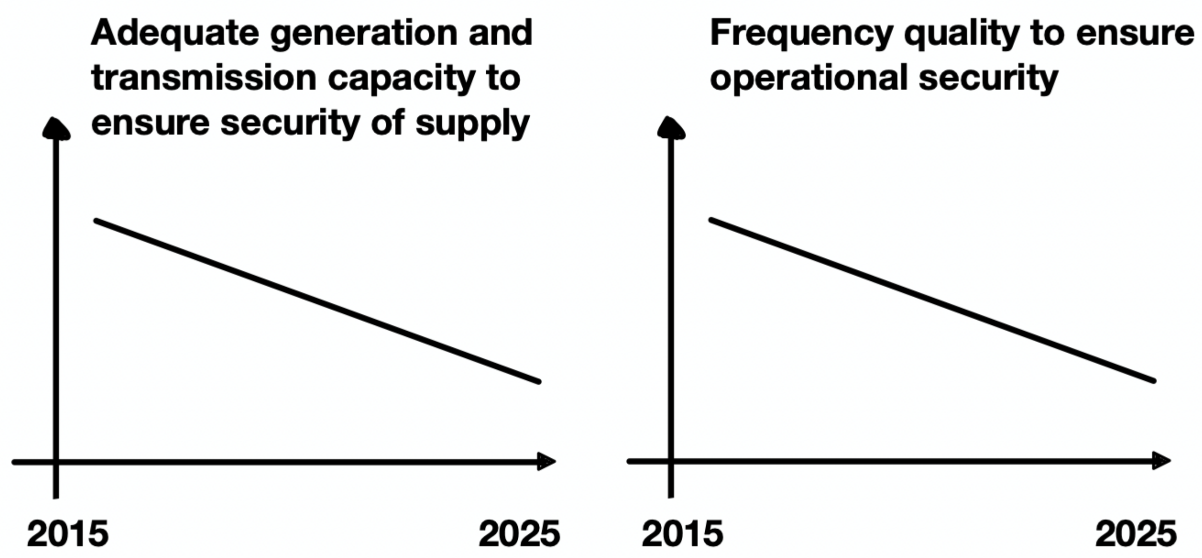

Figure 2.5: a: The generation and transmission capacity will decrease in the Nordic power system from 2015 to 2025. **b**: Frequency quality will also decrease from 2015 to 2025. Inspiration to graphs gathered from lecture by Sonja M. Berlijn [15].

2.4.4 Frequency Quality

The challenges for frequency quality in a power system can in some ways be seen as a combination of the previously presented challenges. Where the frequency is an indication of the power balance in the system, frequency quality is an indicator of system security. This parameter is expected to follow the same trends as the previous ones as can be seen in Figure 2.5.b. The main challenges that have been identified for the future power system in the Nordics with regards to frequency quality are an increased amount of imbalances caused by for example forecast errors and less availability of balancing reserves. Also having a time resolution that is not small enough (updates every hour), meaning changes that happen in between updates are not identified by the market. Smaller power plants and an inadequate transmission capacity reduce access to the balancing reserves because smaller plants do not provide as much as larger plants do. Less transmission capacity reduces the ability to transfer reserves from one place to another. One possible solution to increase the system security that was identified is to develop more information and communication technology (ICT). These are solutions increasing the supervision and control systems, while also introduce more automation into the operational process. Another solution is to apply a finer time resolution into the markets [12].

2.5 RDI Roadmap

The RDI roadmap is a planning tool for the research, development and innovation (RDI) priorities of ENTSO-E from 2020-2030. It highlights the prioritized areas in transmission and power production that need new research and innovation. These areas are highlighted based on the incorporated TSO's needs, technological trends and new operational needs. The roadmap is split into three clusters representing the primary concerns of the future power system and six flagships, which are the use-cases to support the transformation of the energy system [16]. The full overview can be seen in Figure 2.6.

Cluster 1 is organized into flagship 1 and 2 working towards creating "One System of Integrated Systems" where there will be much more integration across sectors. The main focus is to increase the coordination between different energy systems but also TSOs, DSOs (Distribution System Operators), customers and other market participants. Cluster 2 emphasizes upgrades to the current power grid and how to better utilize the current grid to handle the future market demands coming from increased integration. Flagship 3 is the only flagship in cluster 2. Better integration of HVDC and offshore power into the power grid, as well as development on the digital infrastructure and control center operations are the main points of cluster 3. This cluster has flagships 4-6 as its use cases [16].

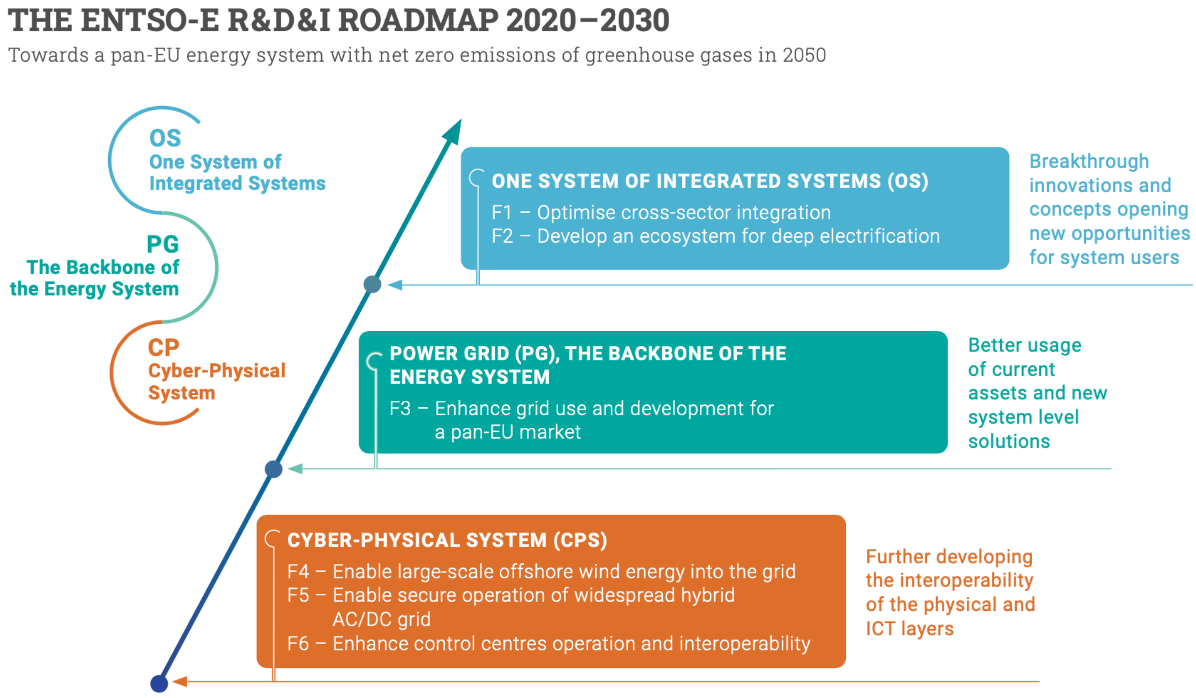

Figure 2.6: The ENTSO-E roadmaps three clusters and their accompanying flagships [16].

For this thesis, the main focus is on the future of operations in the control centers and the use of digital infrastructure to increase system security. Hence flagship 6 is most relevant. With both the generation and load sides of the power system becoming more complex, TSOs will begin to heavily rely on ICT infrastructure to have better control capability and system monitoring. In addition, the system is also becoming more interconnected and is going to include both micro-and mega-grids [16]. Consequently, a challenge arises as not all these actors have the same level of security in their IT-systems, which then leads to a higher risk of cyberattacks [16]. There will also be an increased need for standardized data protocols and vendor-independent solutions because this allows software and hardware to work together no matter who created them. It also works towards a pan-European power grid, which is one of the goals of ENTSO-E. Flagship 6 is trying to improve the accuracy of system operations through better ICT infrastructure and digitization, but must also work hard towards mitigating the risks for increased cyber-attacks at the same time. Figure 2.7 illustrates the milestones in flagship 6, and in the scope of this thesis "Phasor Measurement Unit (PMU) usage for Wide Area Monitoring (WAM)" is central together with "Enhanced methods for more accurate and wider representation of the grid". Building a "resilience toolbox" for the operators in the control centers to assist them can also be considered relevant. A collaboration project between the Nordic TSOs that seeks out to tackle some of the problem areas with the current state of systems operations is NEWEPS. The two milestones mentioned are very closely related to this project.

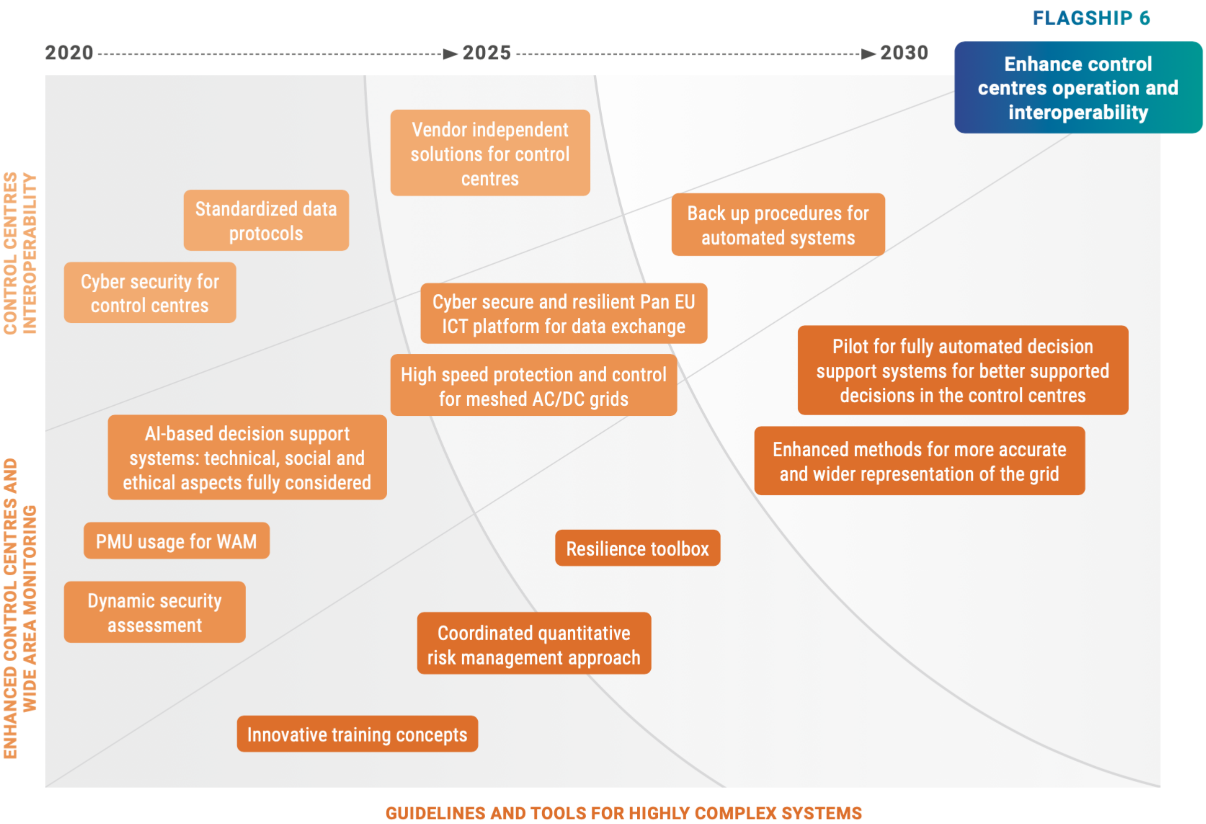

Figure 2.7: The full overview of flagship 6, showing all of the milestones in it [16].

3. NEWEPS, PMU & SCADA

3.1 NEWEPS

The New Early Warning Early Prevention System (NEWEPS) is a collaborative project between the Nordic TSOs to create a prototype of the early warning and protection system to be used by TSOs in the future. This system should have a modular structure, meaning that as new monitoring and control applications are developed they can be implemented easily into the system. Furthermore, all of these models should interact with interfaces that have standardized protocols, which again means that new applications and processing methods can be added later without having to change the core of the system [8]. The main goal of this prototype is to develop and demonstrate control and monitoring methods in the Nordic system, and also mature applications for control, monitoring and protection to later be used by TSOs. Figure 3.1 shows the theoretical run-down of the new system. Oscillation and voltage stability are highlighted as the main assessment modules for the system state. The system data going into the assessment modules is mainly going to come from PMU and SCADA measurements.

The whole project is divided into nine work packages (WPs), each with a main focus area. In this thesis, the main focus will be on WP5 ("Oscillation monitoring assessment"). The goal for this WP is to develop applications (working prototypes) for the monitoring of electromechanical oscillations in the power system. More specifically identifying the source and characteristics of the oscillations as well as suggesting control actions to reduce the significance of these oscillations. The applications should also give proper input to aid in the visualization of its system state [8]. The WP also differentiates between natural and forced oscillations as well as resonance effects. Natural oscillations are constantly present in the system and will limit the power transfer capacity of the system. In the most severe cases where these are not damped, they can lead to collapses in parts of the system or the system as a whole. Forced oscillations are related to poorly tuned control systems or faulty operating components. In most cases, these pose a threat to different components in the grid, but in some cases, they can also be dangerous for the system itself. Resonance effects are when the forced oscillations frequency is close to the natural modal frequency

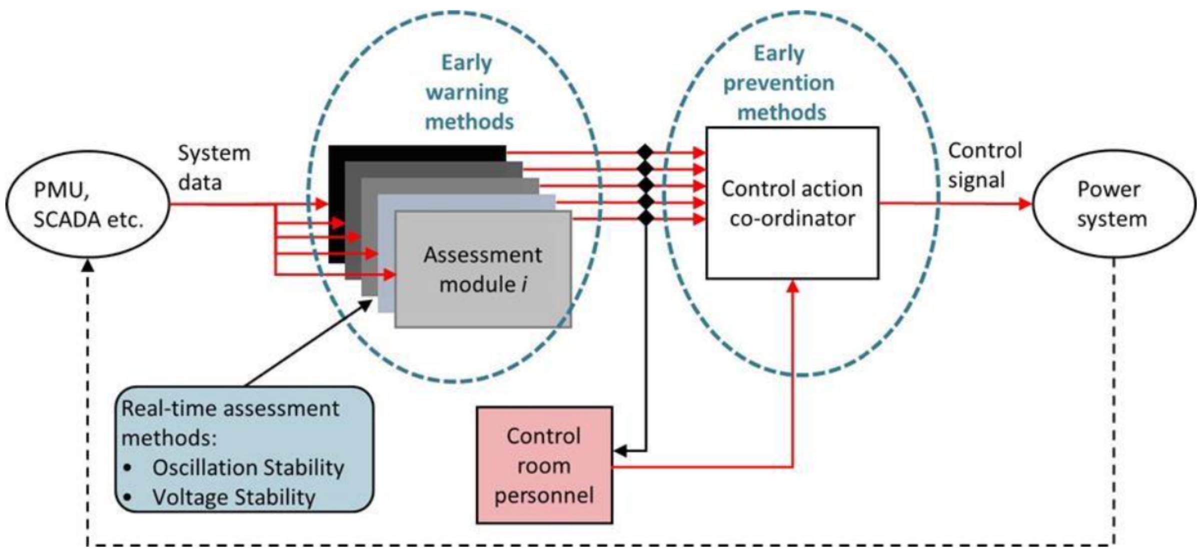

Figure 3.1: A conceptual overview of NEWEPS. The goal is to get real-time estimate of the security and stability of the system. To gain this estimate oscillation and voltage stability is used [17].

of the system and can pose a serious threat to the power system. In this thesis, the main focus will be on the detection and identification of forced oscillations. The applications developed will use system information coming from PMU and SCADA measurements, with the aid of simulations if that is necessary [8].

3.2 PMU and SCADA

3.2.1 Synchrophasors

Synchrophasors are time-synchronized measurements of quantities that can be described by phasors [6]. In power systems, a phasor is usually used to represent either current or voltage signals. A phasor is a very good way of presenting a sinusoidal wave signal because it shows both the magnitude and the phase angle. If the signal is a sinusoidal wave on the form

$$V(t) = V_m sin(\omega t + \delta), \tag{3.1}$$

where V_m is the maximum magnitude of the voltage signal (V_{max} in Figure 3.2.a), ω is the angular frequency, which also can be represented by $2\pi f$ (f is the system frequency). δ equals the angle between the maximum value of the sinusoidal wave and the time reference axis. (3.1) depicts the blue striped line in Figure 3.2.a.

Usually voltage and current is represented by their rms values (green dotted line in 3.2.a)

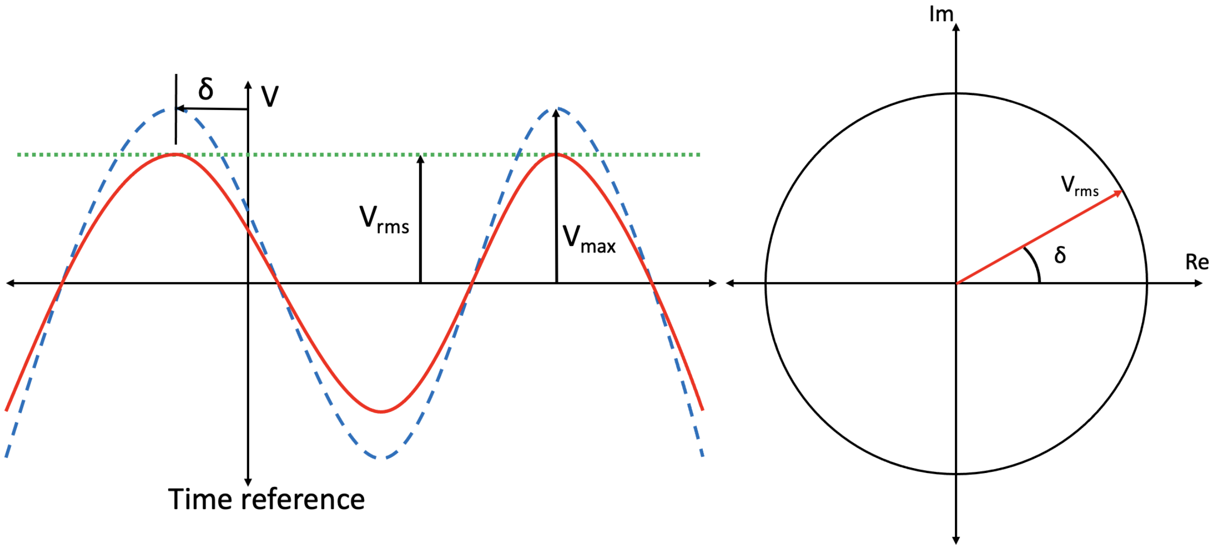

Figure 3.2: **a**: The left figure shows a sinusoidal curve for a voltage signal. **b**: On the right is the phasor diagram for the sinusoidal curve.

and the relationship between the rms value and the max value is as follows:

$$V_{rms} = \frac{V_{max}}{\sqrt{2}}. \tag{3.2}$$

Then the sinusoidal wave (3.1) can be written as

$$V(t) = V_{rms}sin(\omega t + \delta). \tag{3.3}$$

(3.3) is represented by the red line in Figure 3.2.a and corresponds to the phasor shown in Figure 3.2.b. Here the length of the phasor is equal to the rms value for the sinusoidal wave. On polar form this phasor is written as

$$V = V_{rms}e^{j\delta}. \tag{3.4}$$

3.2.2 SCADA

Supervisory Control and Data Acquisition or SCADA is the most used system for state estimation (SE) in current power systems [5]. In the SCADA system, sensors, such as Remote terminal units (RTUs), collect data. This data is then supplied to Master Terminal Units (MTUs) and/or Programmable Logic Controllers (PCL) and further on to the system operators. The RTUs have a relatively slow sample rate at once every 2-10 seconds (depending on the system), which makes them mostly used for static SE. If static SEs are used then it is assumed that the system will not change from one measurement to another. This is the most widespread state estimation method used. All the data collected through the SCADA system is often stored in SQL-databases so that further investigations and research can be done after an event has happened to help prevent it from happening again [18].

Due to the increased share of renewable energy sources in the generation mix and more variable loads, many TSOs and distribution network operators (DSOs) want to implement more real-time/dynamic state estimation. For this to happen it is paramount to increase the sample rate in the system and being able to synchronize data measurements from different parts of the grid. The current SCADA system is unable to do this, and new sensors have to be integrated into the system. This is where Phasor Measurement Units (PMUs) come in.

3.2.3 PMU

A PMU is a device that measures voltage and current in a power system and represents them as synchrophasors. From these measurements PMUs are also able to calculate the active and reactive power [MW] and [MVAR], as well as the frequency [Hz] and phase angles (δ) [$\frac{\text{rad}}{\text{s}}$]. Being synchrophasors means they are time-stamped with an accuracy on the microsecond level and then synchronized by communicating with for example satellites used in the global positioning system (GPS) [6]. Because of the synchronized nature of PMU data, operators can align data from different positions in the grid and determine the relative phase angles between these positions [5]. PMUs have a much higher sample rate than the traditional SCADA system, around 30-60 measurements per second [6].

3.2.4 SCADA with PMU

By implementing PMUs, system operators will be able to increase the use of dynamic state estimation in the power system. This will greatly increase the responsiveness of the grid to changes in frequency unbalance. As can be seen in Figure 3.3, a PMU will be able to give a much more accurate impression of what is happening in the system than the current SCADA system is. The PMU-data will follow the exact change in the system as it is often set to sample at the same rate as the mode frequency of the grid. By using the current measurement technology only parts of what is happening are being displayed to the system operators [5].

Although it might seem tempting to replace the current SCADA system with PMUs this is too costly as the devices themselves are expensive and with the increase in data one would receive, whole new systems would be required to handle and store it. Therefore PMUs can instead be integrated into the current SCADA system and be used in some areas with a lot of strain, whilst smaller areas can continue utilizing the current system.

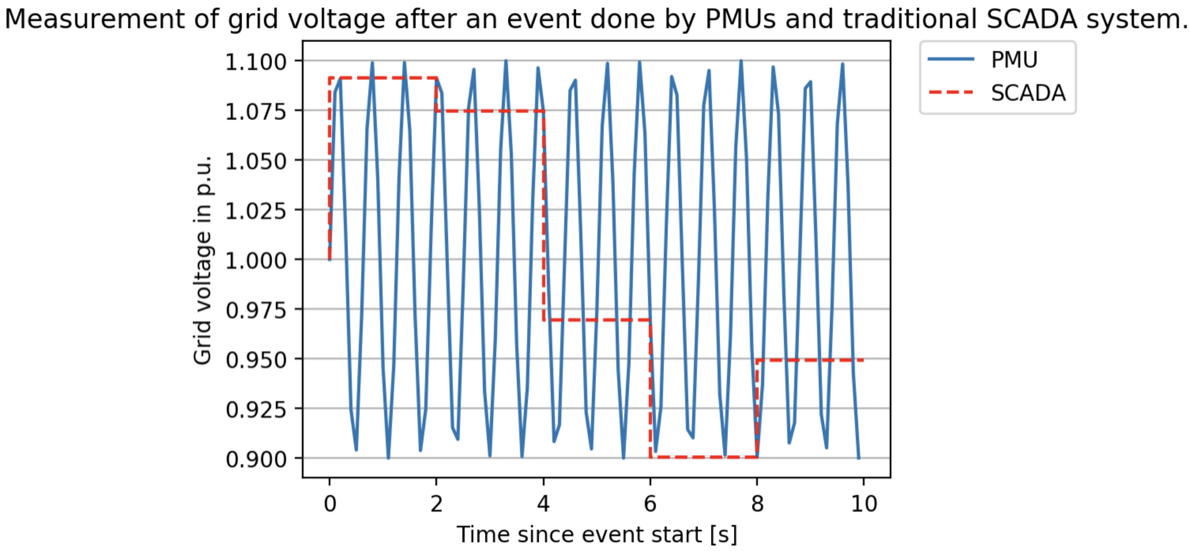

Figure 3.3: Illustration of the sample rate for PMUs vs the current SCADA system after an event in the power system.

This way control will be gained over the areas under stress and at the same time costs will be kept relatively low.

The North American power system is one of the systems with the most widespread usage of PMUs, with almost 1700 PMUs installed across the U.S. and Canada in 2014 [19]. In 2018 that number was closer to 1900 with Mexico also included in the counting [20]. According to an employee working for Statnett, the Norwegian system contained 120 PMUs and the rest of the Nordic countries had an additional 145 PMUs during the spring of 2021. In addition, another 60 PMUs are expected to be installed in the Nordic power system in a short amount of time [21]. Although there are many of them a system operator in Statnett stated that the PMUs in Norway are currently mostly used for post-analytics and research, rather than being implemented in the system operations [22].

4. Methodology

4.1 Literature Studies

The main process of obtaining information in this thesis is through a literature study. For the main theory behind oscillations and PMU both articles and books were used. Articles were mainly gotten from Research gate and Google Scholar, while the book used was "Power System Analysis & Design" [23] from a personal selection. This book together with lecture notes from a university course about power systems [24] was mainly used to understand how oscillations can occur in the power system, and to fill in possible gaps relevant articles were researched. Theory about the types of oscillations was founded on articles found in Google Scholar where the article "Power System Oscillatory Behaviors: Sources, Characteristics, & Analyses" covers the main information.

As WP5 in the NEWEPS project had its focus on both detecting forced oscillations and their characteristics as well as locating the source of the forced oscillation this was used as motivation when choosing which keywords to be used in the literature review. Using relevant keywords together with PMU and forced oscillation several articles were found in Google Scholar and Research Gate where most of them had been posted in IEEE. Although the focus-areas in WP5 do not yield as much literature as other areas of power system information, an acceptable amount of articles were found for both detecting forced oscillations and their sources.

As this is such a short master thesis and a limited amount of time to gather information some limitations have to be set on the literature search. For both detection algorithms and locating methods, one article was chosen as the main source. This was based on certain requirements and the limitations picked with the background knowledge of the NEWEPS project and its goals. Other articles were used to gain a wider view of the different solutions that have been researched and tested, driving the discussion. As stated this is an area with limited amounts of research and thus preliminary searches did not reveal an overwhelming amount of articles. To gain a wider search area, relevant authors were further examined and cited works were explored. After having gained a large cluster of articles some limitations were set to keep a degree of relevance:

- Only research done after 2012 was considered to keep the information relatively new and relevant.
- Possible case studies must use PMU data to show relevance to future power systems.
- Articles regarding general oscillations were ignored to keep the focus on forced oscillations.

4.2 Technology Readiness Level

Technology Readiness Levels (TRLs) are part of a system used to estimate the maturity of technologies that might be adopted by a company. There are nine levels in Statnett's TRL-system as displayed in Figure 4.1 [25]. As FOs have not been a central area of research for the Nordic TSOs this can be given TRL 1 or 2 before the NEWEPS-project begins. This is based on the wording used in the project description. The goal of the project will be to reach levels 5-7. As stated before the outcome of the project should be a prototype of a working concept either used in a relevant (level 5/6) or an operating (level 7) environment. A more detailed explanation of each level can be seen in appendix A.

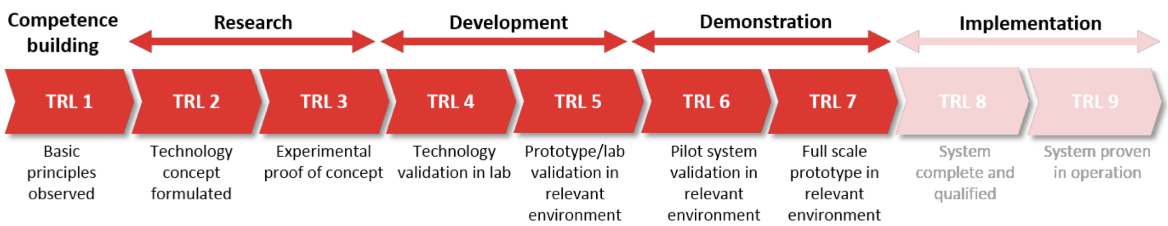

Figure 4.1: The Technology Readiness Level scale, with some simple explanation of each level. The scale is adjusted from Statnetts documentation [25]

4.3 Case Study

To gain a fuller understanding of how forced oscillations are present in the power system a case study will be utilized in addition to the literature study. The goal of the case study will be to gain a visualization of how a forced oscillation can be observed in a frequency versus time representation. This case study will have its focus set on a part of the northern Norwegian power grid. This area is referred to as ”Sørnettet” and is located in the area around the Lofoten archipelago. Where it is located in the Norwegian grid is shown in Figure 4.2. Two substations with a base voltage of 420 kV deliver power out to Sørnettet, where the voltage is transformed down to 132 kV [26], [27].

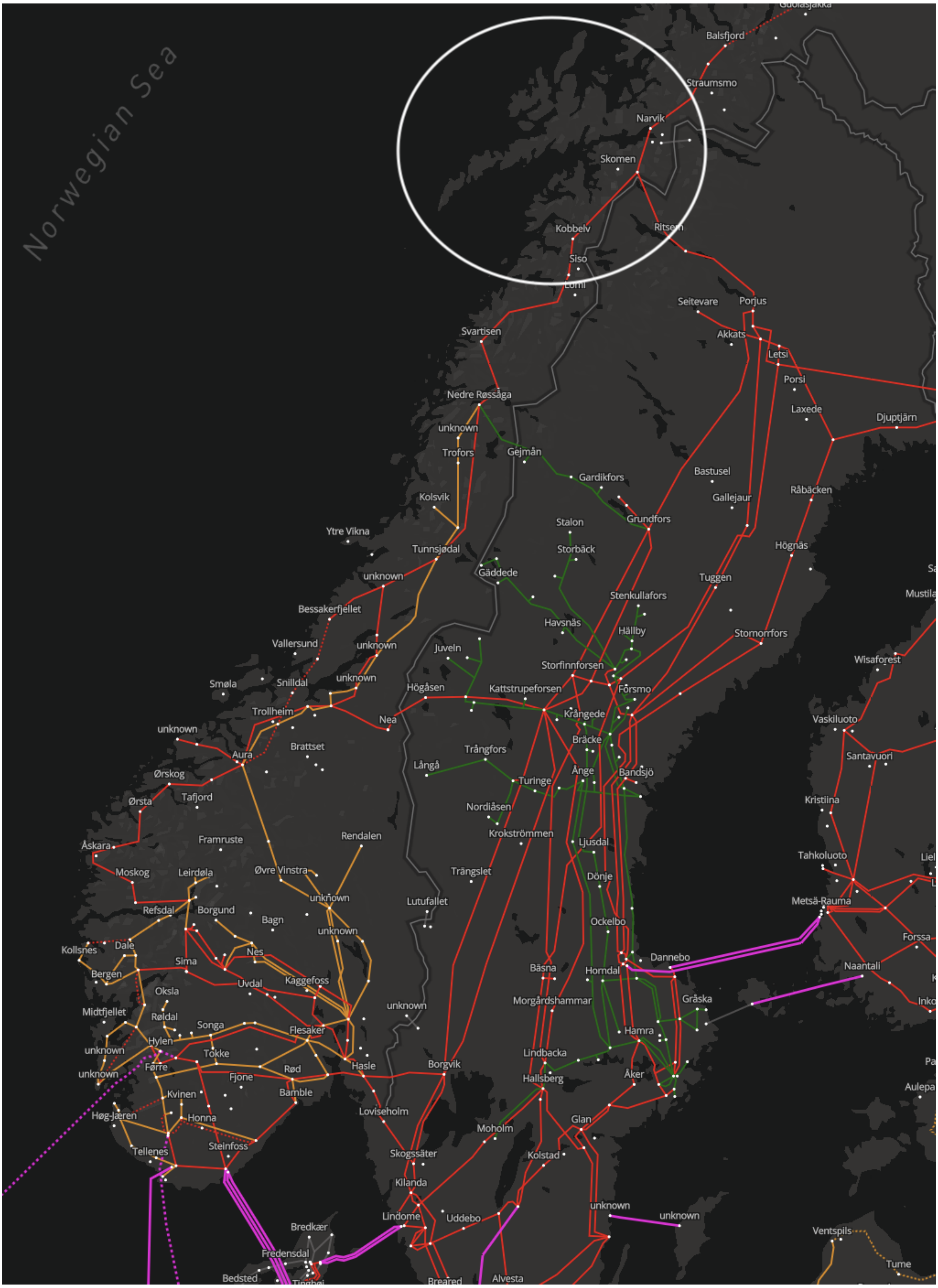

Figure 4.2: Grid map showing the high voltage transmission lines in Norway. The white circle indicate the area of interest to the case study. Gathered from [26]

As power systems typically are very complex, performing large analyses on them can be very time-consuming and unpleasant. Therefore, smaller test systems that resemble the real power system are used to study different phenomena in computer simulations. Similarly, in this thesis, a test system that is very similar to Sørnettet will be used. As the details regarding the full structure of the Norwegian grid are not public domain further information about the test system will be kept anonymous in this thesis.

Simulations will be done in the power system analysis tool PSS/E, created by Siemens. This software is a great tool for use in power system analysis as it contains a significant amount of analyzing features, such as dynamic simulations, power flow and contingency analysis. As a novice in this program, a great amount of time was spent trying to acquire the skills necessary to perform a suitable analysis. For this, the user manual of PSS/E was of great use [28]. The case study and its results will be further discussed in Chapter 6.

5. Power System Stability and Oscillation Theory

5.1 Power System Stability

A power system's ability to move between two steady-state operating points, separated by a disturbance, without experiencing unacceptable voltage magnitudes and frequency deviations, or losing synchronism in any generators can be referred to as power system stability [23, p.669]. In both [23, p.682] and [29] a proposed definition of power system stability is quoted from IEEE/CIGRÉ Joint Task Force on Stability Terms and Definitions in 2004 as:

> "...the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variable bounded so that practically the entire system remains intact."

An interpretation of this is that the power system must be able to withstand a disturbance and return to steady-state without losing any significant equipment. In [23, p.669-671] it is stated that there are three types of power system stability:

- steady-state stability
- transient stability
- dynamic stability.

The slow and gradual changes in an operating point can be defined as steady-state stability. The goal of studies in this area is to ensure that phase angles across transmission lines are not too large, that important equipment like generators, transformers and transmission lines are not overloaded and that bus voltages stay close to their nominal values. If (5.5) is at its maximum point ($\delta = 90°$) the maximum power a line can deliver is reached and this is the theoretical steady-state stability limit. If this is overreached asynchronism would occur between synchronous machines at the sending and receiving end [23, p.669-671].

Transient stability is the case where larger disturbances, such as faults, sudden load changes and loss of generation occur. The objective in studies about transient stability is to determine whether or not machines will recover from deviations from the synchronous frequency (50 Hz in the Nordic system) with new steady-state power angles. If a disturbance lasts for several minutes then it would be regarded as a dynamic stability study rather than a transient one.

The focus of [29] is rather to split power system stability into three subcategories: Rotor angle stability, Voltage stability and Frequency stability. The three categories together with further categorization are shown in Figure 5.1.

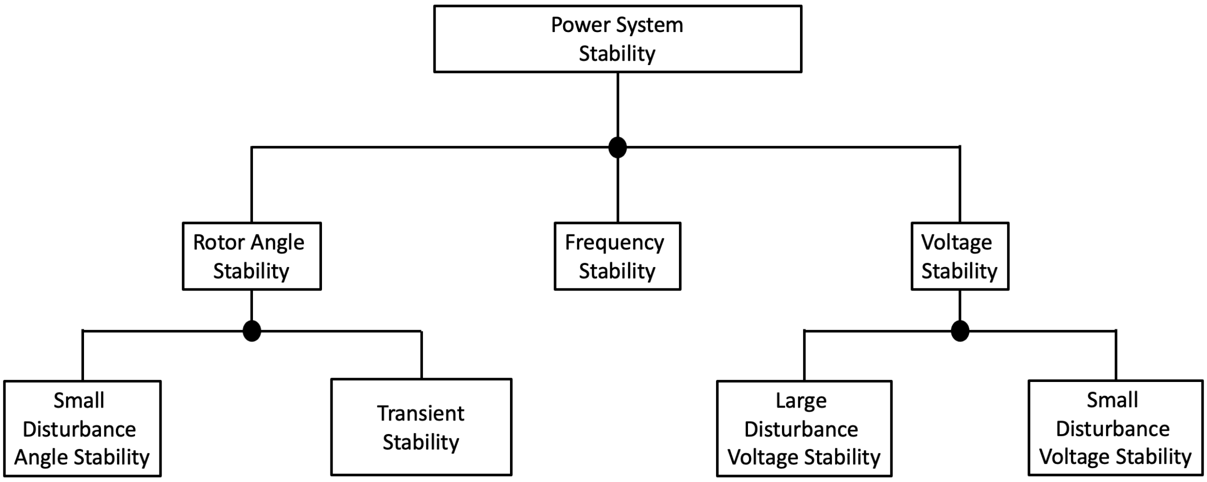

Figure 5.1: Classification of the different types of power system stabilities. Inspiration for the flowchart gathered from [29].

Voltage stability can be defined as a power system's ability to maintain stable bus voltage on all the buses in the system after a disturbance occurred. It can further be divided into large and small disturbances. Large disturbances are connected to transient stability from above as it is classified by system faults or loss of generation, while small disturbances encompass smaller variations in system load and fall under steady-state stability [29]. In normal operations, power consumption should never reach the steady-state stability limit as this can lead to voltage collapses.

Similarly, frequency stability can be defined as the ability of the power system to contain stable frequency after large disruptions in the balance between generation and load take place [23, p.682]. In power system's operations, there are usually set boundaries where the frequency should not exceed. The Norwegian TSO, Statnett, has a working boundary of 49,90-50,10 Hz under stable operations [30].

The third stability category, rotor angle stability is defined as the ability of a synchronous machine to maintain its synchronism after a disturbance. Thus the machines must be able to keep or bring back equilibrium between the electromagnetic input torque and mechanical output torque. If equilibrium is not reinstated quickly this absence of synchronism in the machine can cause electromechanical oscillations in the power system. As can be seen in Figure 5.1 it can be further split into small disturbance angle stability and large disturbance angle stability (or, as stated by the authors, transient stability) [29]. Small disturbance can be related to steady-state stability as it is concerned with small disruptions in the system and can be associated with insufficient damping of oscillations. The time frame in question is 10-20 seconds after a disturbance occurs.

Large disturbances fall under the type of transient stability and are therefore often referred to like this in the literature. It is concerned with larger disturbances such as short circuits on transmission lines. The time frame is usually only 3-5 seconds after such a disturbance. In the following section, transient stability as a type of power system stability (and not a subcategory of rotor angle stability) will be discussed. Of the three classifications of power system stability, the main focus of this thesis will be on rotor angle stability.

5.2 Transient Stability

Previously it has been mentioned that having a stable power system is essential for assuring reliable power supply to consumers and making sure that all electrical components connected to the system are not put in danger of being used outside their drift characteristics. Which could be dangerous because it can cause the components to break. In the Nordic power system, this is equivalent to containing a frequency equal to 50 Hz. If the system can uphold stability as sudden large disturbances, like generator or load tripping, it can be seen as transiently stable. In a very analog way, this can be visualized using a ball in a bowl as seen in Figure 5.2. In the figure, the ball is in stable equilibrium, and any movement from this position can be seen as a change in the voltage angle in a power system. Doing a stability analysis is looking for how much a voltage-angle can change before we are no longer in stable equilibrium (when the ball falls out of the bowl) [24].

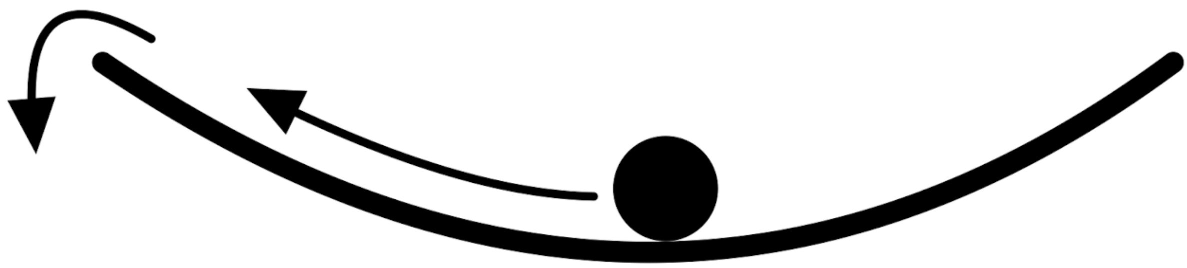

Figure 5.2: Illustration of a ball in a bowl, arrows representing change from equilibrium and the time when there is no longer stable equilibrium (Inspiration for illustration from lecture by Heidi S. Nygård [24]).

It is important to know how large disturbances a generator can handle and whether equilibrium will be restored within an acceptable time. Electrical generators have a certain amount of energy, stored in the rotating masses, which can exchange from potential to kinetic energy. They also have a dampening-force/friction, so the system will eventually fall back into equilibrium position if the disturbance is not too large. Using the swing equation (5.1) the rotor dynamics of a synchronous generator is described and equally the transient stability of the system.

$$\frac{2H}{\omega_{syn}}\omega_{p.u.}(t)\frac{d^2\delta(t)}{dt^2} = p_{mp.u.}(t) - p_{ep.u.}(t) = p_{ap.u.}(t), \tag{5.1}$$

where $p_{mp.u.}$ is the mechanical power supplied by the prime mover minus mechanical losses [per-unit] and $p_{ep.u.}$ is the electrical power output of the generator plus electrical losses [per-unit]. δ is the power angle, ω_{syn} is the synchronous electrical radian frequency calculated from the system frequency (f) using

$$\omega_{syn} = 2\pi f. \tag{5.2}$$

The per-unit electrical frequency is given by

$$\omega_{p.u.}(t) = \frac{\omega(t)}{\omega_{syn}}, \tag{5.3}$$

where $\omega_{p.u.}(t)$ is electrical radian frequency and is often assumed to be 1.0 for hand calculations because the rotor speed ($\omega(t)$) does not vary significantly from the synchronous speed during transients [23, p.690-691]. H is the normalized inertia constant and is defined by the following

$$H = \frac{\text{stored kinetic energy at synchronous speed}}{\text{generator voltampere rating}}. \tag{5.4}$$

When a synchronous motor is running in steady-state conditions the mechanical power input and the electrical power outputs are equal resulting in a net accelerating power ($p_{ap.u.}$) equaling 0. As H normally falls in a range of 1 to 10 $\frac{\text{p.u.}}{\text{s}}$, $\omega_{p.u.}(t)$ is as stated often assumed to be equal to 1.0 and ω_{syn} is the angular velocity of the rotor when it runs synchronously the only way to make the left-hand side of (5.1) equal 0 is if the double derivative of the power angle equals 0 [23, p.690].

If the generator terminals short circuit this could lead to $p_{ep.u.}$ dropping to zero, which would result in a positive net accelerating power. As H, ω_{syn} and $\omega_{p.u.}(t)$ are constants in a generating unit this will hence lead to a positive $\frac{d^2\delta(t)}{dt^2}$. Such a positive angular acceleration leads to a positive radian frequency and an increase in the power angle in the generator.

Looking at a generating unit connected to a power system like the circuit diagram in Figure 5.3 it is clear to see that they have a constant internal voltage, E', and a transient reactance X'_d. V_{bus} is a representation of the transmission lines, transformers, loads and other machines in the power system and is here an infinite bus. The phase angle, δ, is the machine's power angle with respect to the infinite bus [23, p.695].

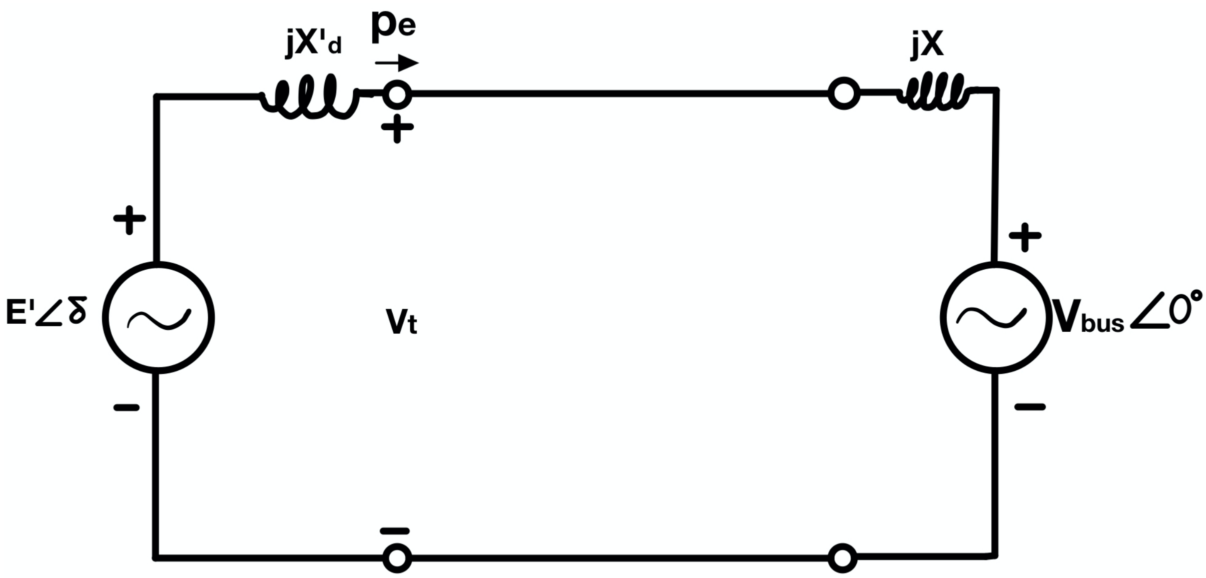

Figure 5.3: Circuit drawing of a synchronous generator connected to a power system represented by an infinite bus. Illustration is modified from Figure 11.3 in [23, p.695].

The electrical power output from the generating unit, depicted by p_e in Figure 5.3 can be calculated using

$$p_e = \frac{E' V_{bus}}{X_{eq}} \sin(\delta), \tag{5.5}$$

where $X_{eq} = (X'_d + X)$. In transient stability problems both E' and V_{bus} are assumed to be constant, which means that the real power delivered from a generator to a power system is a function of the power angle. The mechanical power input to the generator can usually be thought of as not changing for smaller disturbances, but it can in some instances be changed by the operators. Analysis of what happens to the power angle when there is a change in either the mechanical power input or electrical power output can be done using the Equal-Area Criterion [23, p.696-697].

The Equal-Area Criterion is only usable when looking at one generating unit connected to a system (as in Figure 5.3). If more machines are connected then solving the nonlinear swing equation using numerical integration is needed, but that will not be looked at in this thesis. If it is assumed that the mechanical power is kept the same, unless changes are induced by operators, and the electrical power output is modeled using (5.5) then these can be plotted against the power angle as in Figure 5.4. The point where $p_{ep.u.}$ and $p_{mp.u.}$ cross on the left side is the equilibrium point for that generating unit and the power angle is δ_0. This value will vary between different generating units.

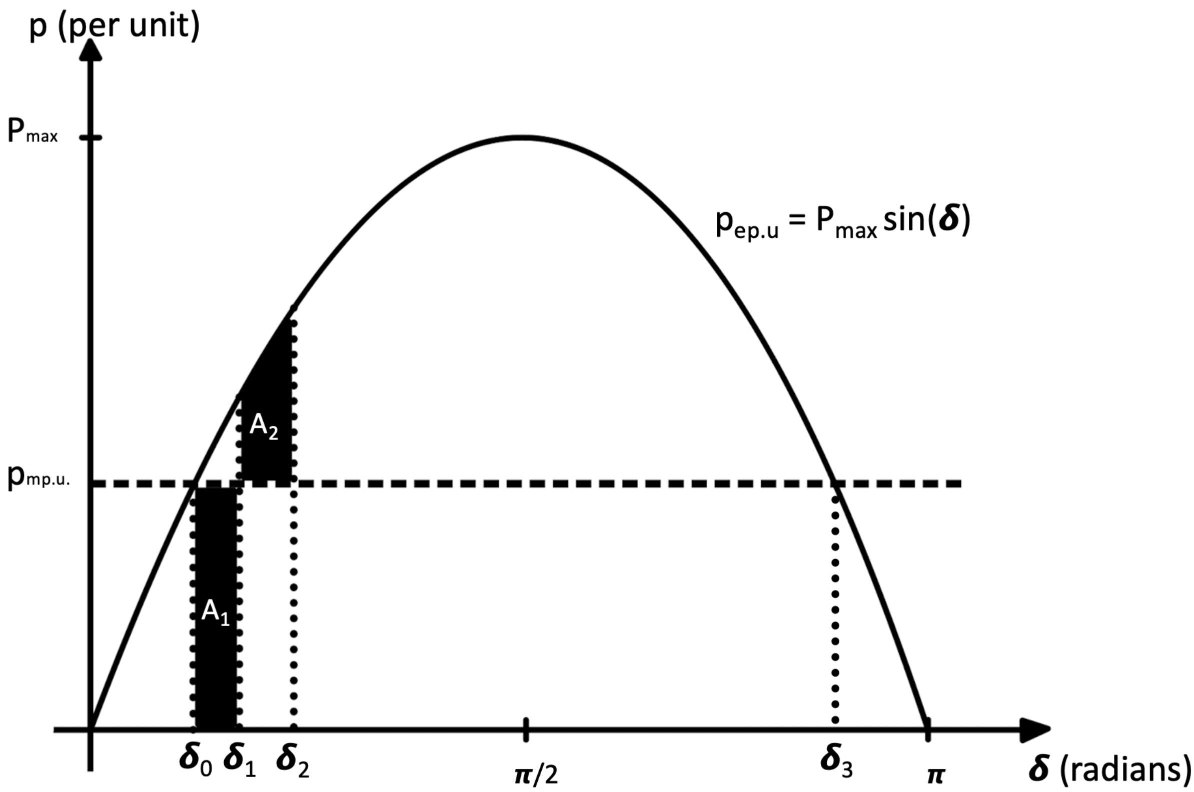

Figure 5.4: Electrical power, $p_{ep.u.}$, and mechanical power,$p_{mp.u.}$, plotted against power angle, δ. Illustration is modified from Figure 11.7 in [23, p.700].

When a disturbance happens, say for example the generator terminals are short-circuited again, and $p_{ep.u.}$ drops to 0. As stated before this will lead to a positive acceleration power and from (5.1) the angular acceleration will also be positive. Therefore the rotor will start to accelerate and δ starts to increase from δ_0 towards δ_1. In Figure 5.4 δ_1 is where the fault causing the disturbance extinguishes and $\frac{d^2\delta(t)}{dt^2}$ returns to zero. However $\frac{d\delta(t)}{dt}$ is still positive and therefore the power angle will continue to increase. Now the electrical power is greater than the mechanical power and the result is a negative $\frac{d^2\delta(t)}{dt^2}$, which in turn will decrease $\frac{d\delta(t)}{dt}$ and δ will eventually stop at δ_2. At this power angle, the electrical angular acceleration is still negative and the power angle starts to decrease. With no damping in the system, this process will keep oscillating between δ_0 and δ_2, which results in the electrical power output to the grid oscillating between values determined by (5.5). Such an oscillating output can be harmful to other components in the grid and so it is very important to try and stop them from happening.

Another problem that can arise is not being able to maintain stability for the synchronous machine. If the power angle were to surpass δ_3, $p_{mp.u.}$ would again be greater than $p_{ep.u.}$ resulting in the rotor wanting to rotate faster. Where this to happen the machine would reach the point of rolling over the edge of the bowl in Figure 5.2 and stability would be lost. Hence it can be useful to compute the critical clearing time, which is the time an operator has to fix the fault before the machine spins out of control. Here the equal-area criterion is very powerful and useful. On page 698-699 in [23] it is shown that A_1 must equal A_2 and as δ_0 is a characteristic of the generating unit and $\delta_3 = \pi - \delta_0$, this mathematical equality can be used to find the critical clearing angle using

$$\int_{\delta_0}^{\delta_{cr}} (p_{mp.u.} - p_{ep.u.}) d\delta = \int_{\delta_{cr}}^{\delta_3} (p_{ep.u.} - p_{mp.u.}) d\delta. \tag{5.6}$$

The usage of the equal-area criterion as shown in (5.6) is shown in Figure 5.5. Further along the swing equation (5.1) can be solved and rewritten to obtain the time available to fix the fault before stability would be lost.

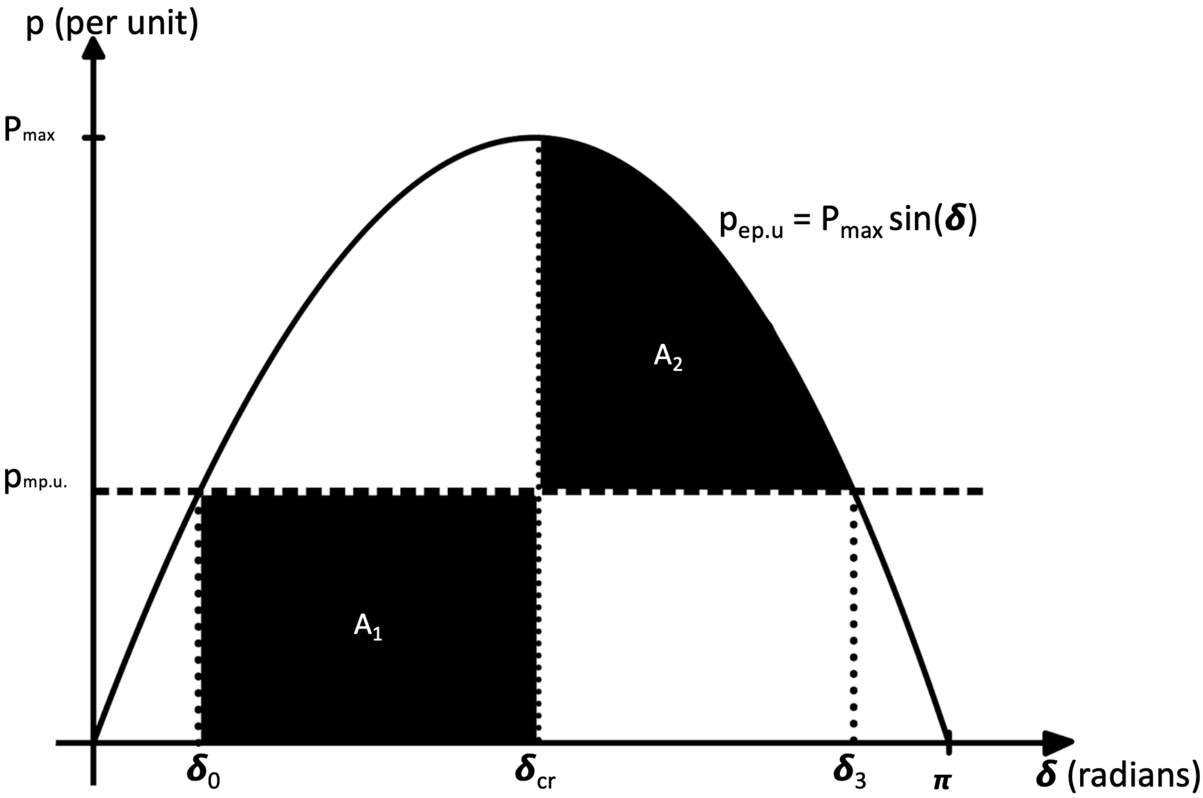

Figure 5.5: Electrical power, $p_{ep.u.}$, and mechanical power,$p_{mp.u.}$, plotted against power angle, δ. Usage of equal-area criterion to obtain the critical clearing angle δ_{cr}. Illustration is modified from Figure 11.10 in [23, p.703].

In all instances where a disturbance has occurred but is then repaired within the critical clearing time, the output of the machine will oscillate between two levels determined by the power angle values. If the system does not contain any inertia or dampening then the oscillation will continue until the machine is manually shut down. This can be dangerous for other units connected to the system if these are very sensitive to variable electrical power input. It is therefore imperative that the system contains a certain amount of inertia to stabilize the system after a fault.

If the system contains inertia then a dampening term must be subtracted from the right-hand side of the swing equation and hence (5.1) will become

$$\frac{2H}{\omega_{syn}}\omega_{p.u.}(t)\frac{d^2\delta(t)}{dt^2} = p_{mp.u.}(t) - p_{ep.u.}(t) - \frac{D}{\omega_{syn}}\frac{d\delta(t)}{dt} = p_{ap.u.}(t), \tag{5.7}$$

where the dampening term is proportional to the speed deviation from its synchronous speed and D is usually either zero (the cases that have been studied until now) or a relatively small positive value with units per unit power over per unit speed deviation [23, p.691]. When using (5.7) the graphs like the one in Figure 5.4 will oscillate between δ_0 and δ_2, but over time it will stabilize at δ_1.

5.3 Types of Oscillations

As stated before oscillations are a response to faults or changes away from the current steady-state of the system. Therefore they are often referred to as responses instead of oscillations. In general, there is considered to be three main responses, namely ambient, transient and forced responses [7]. Typically ambient and transient responses are grouped and called natural responses.

- **Natural responses**
  The characteristics of natural responses are determined by the system itself. The oscillatory modes are functions of the operating conditions and they are characterized by the frequency, damping and shape of the modes. Examples of ambient and transient responses are:
  - Ambient responses such as small random load changes or system switching effects.
  - Transient responses: sudden disturbances such as line, generator, or load tripping.
- **Forced responses**
  These are characterized by the external inputs from the machines or apparatus that

are malfunctioning [7]. Examples can be an arc furnace inducing its dynamics to the system or a malfunctioning steam valve cycling on and off.

5.3.1 Ambient Responses

When the system is responding to small random changes, like system switching effects, varying generation loads, system load and smaller disturbances, these may be called ambient responses. These changes affect the outputs produced by the PMUs in the power system [7]. If a model is set up where the input is the random changes then the output would be the measurements from the PMUs. Analyzing the output in the frequency domain using the Power Spectral Density (PSD) gives a great deal of insight. An example of a PSD is displayed in Figure 5.6, the peaks represent the electromechanical modes of the system. The range of low-frequency oscillations depends on whether it is a local or inter-area mode. Local modes come from one generator swinging against the rest of the system (as in Figure 5.3) and typically have a frequency range of 1-2 Hz. Inter-area modes are the swinging of several machines in one area against several other machines in another area and have a frequency range from 0.1 to 1.0 Hz [31]. The location of the peaks in a PSD corresponds to the frequency in which the response oscillates. The PSD in 5.6 was created using an input containing three sinus curves with different oscillating frequencies and random white noise and then running a fast Fourier transformation to isolate the main frequencies of the input signal [7].

Further analysis of the electromechanical modes found can be done using numerical methods in both time and frequency domain, but this is outside the scope of this thesis and can be found in [7] for interested parties. If when looking at the system on a time scale the observed responses have large deviations from the normal value there is no longer talk of ambient responses.

5.3.2 Transient Responses

Transient responses occur from system events rather than being present at all times in the power system and will die out after some time, with the scale varying from event to event. Transient responses also fall in the category of natural responses together with ambient noise, but as can be seen in Graph 5.7, they are very different. Examples of events that can occur are generation losses, load tripping and faults or trips on transmission lines. The transient response is how the power system can settle back to the steady-state conditions after the fault will cause an excitation in the system [7]. Transient responses can be analyzed using several different methods. Mostly time-domain analysis and eigenvalue analysis is used, either together or separately. Another alternative is Prony analysis which is an extension of Fourier analysis and can give dampening and frequency information [31].

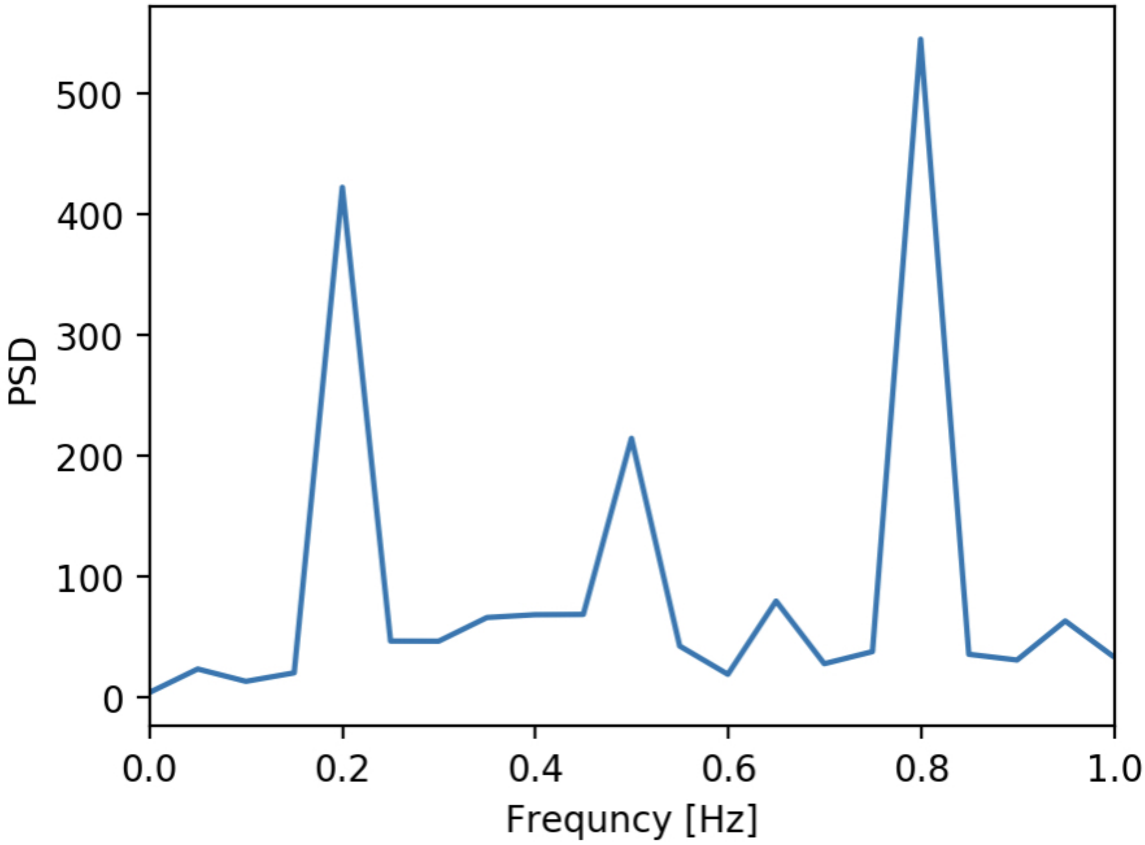

Figure 5.6: A power spectral density showing the main frequencies of an input signal containing some white noise. The main frequencies of the input signal are 0.2, 0.5 and 0.8 Hz.

[7] uses Prony's method in a time domain to analyze transient responses, while [31] briefly describes all three and uses eigenvalue analysis on an example model.

5.3.3 Forced Responses

As stated before there is also a third type of oscillation present in power systems. This type is not characterized by the system but by the input driving the oscillation. They are called forced responses and they can be introduced by several different scenarios such as malfunctioning control units or physical components inside a generation plant [7]. [32] presents several forced oscillation sources that have been observed in the western North American Power System. Forced responses can vary greatly in their characteristics, meaning that some are easily identified in time domain measurements, while others are not detectable in PMU data unless an attentive examination is carried out [7]. The inputs creating the forced oscillations are harmonic in nature and can be expressed using Fourier series, such as

$$u(t) = \alpha_0 + \Sigma_{h=1}^{\infty} \alpha_h \cos(h\omega_0 t + \theta_h), \tag{5.8}$$

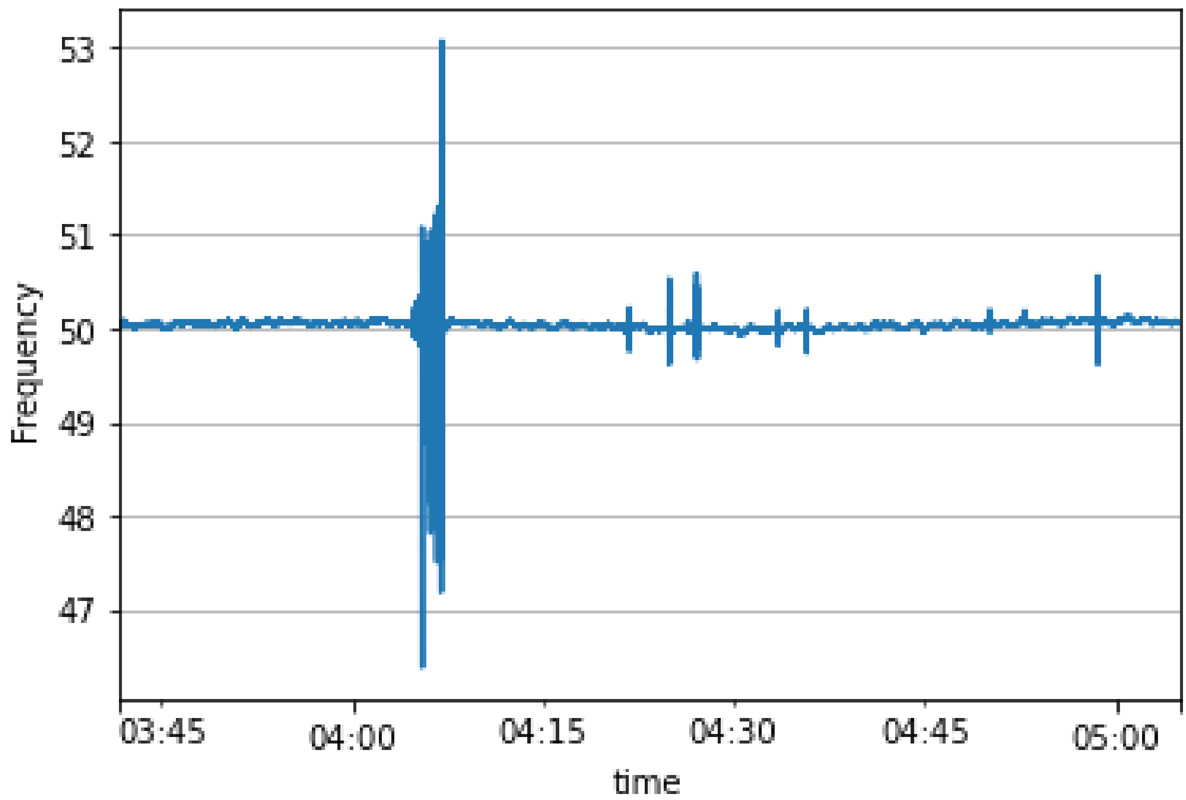

Figure 5.7: This graph is showing ambient responses in a power system together with one huge transient response and a couple of smaller transient responses.

where each term is harmonic and ω_0 is the fundamental frequency with $[\frac{\text{rad}}{\text{s}}]$ as units [7]. α_0 and α_h are real numbers and how these coefficients are calculated can be found in [33, p.102]. Although forced responses are not resulting from system operations they are affected by them, and therefore the measured output signal will not reflect the same waveform as the input, but can rather be modeled by

$$y_{i,u}(t) = G_i(0)\alpha_0 + \Sigma_{h=1}^{\infty}|G_i(h\omega_0)|\alpha_h \cos(h\omega_0 t + \theta_h + \angle G_i(h\omega_0)). \tag{5.9}$$

In (5.9) $G_i(\omega)$ is the transfer function between the input where the forced oscillation is coming from and the output i. The frequency components will still be preserved although the signal will look different in the time domain, which makes it possible to spot the harmonics of the input signal in the output as well. Another characteristic of forced oscillations is that they do not contain dampening in the same way as natural responses do, which in many cases can help identify them as it is very uncommon for natural responses to be undamped. But even as they are undamped their amplitude may differ in time as changes happen in the driving input. As mentioned the output signal that is measured by PMUs will in most cases be different from the input signal coming from the driving unit into the signal. The gain and phase shift that is applied to the forced oscillations as it passes through the system (expressed by (5.9)) is dependent on the path the oscillation takes through the grid. In most cases, the forced oscillation is observed to be the largest closest to the source of the oscillation, but in certain systems, this might not be the case and the oscillation can travel and have larger amplitudes in other parts of the system. This can make it harder to detect where the forced oscillation is originating from [7].

One of the biggest dangers with forced oscillations is that they can resonate with electromechanical modes in the power system, which can lead to significantly larger oscillations in other parts of the system. [34] did several tests on what causes the greatest resonance effects between system modes and forced oscillations. It was found that having a well-damped system is very important as the effect of resonance is significantly smaller on electromechanical modes with higher dampening characteristics. The location of the forced oscillation was also found to be important. Imposing a 10 MW forced oscillation with the same frequency as a system mode with low dampening (set to 1.9%) could in one case cause a 477 MW oscillation at another part of the system, which can lead to system blackouts and damaged system equipment [34]. As forced oscillations are not an inherent characteristic of the system itself, but often originate in faulty equipment, to negate them the equipment has to be fixed. Therefore it is also very important to be able to not only detect the presence of forced oscillation but also locate where in the system the fault is located.

6. Case study

6.1 Creating a Forced Oscillation

As mentioned in Chapter 4 the purpose of the case study will be to try and visualize some characteristics of FOs in a power system. Towards the end of Chapter 5 it was presented that forced oscillations often have the highest amplitude in the area where they are originated. This is the characteristic that will be explored in the case study. The theory also states that forced oscillations occur when a generator or controlling equipment experience a fault, creating periodic signals.

In consultation with a senior researcher at Statnett, it was decided that to simulate a forced oscillation in PSS/E the load power demand of an area in the test system will be increased and decreased with a certain frequency. This oscillation will then be observable in the frequency vs time graph for that area. Furthermore, while running a dynamic simulation and monitoring several nodes in different areas the theory that an FO is most dominant near the driving input can be tested.

Two nodes in the test system will be set as measurement nodes, where the frequency will be measured and visualized. Then two different scenarios are to be tested. In the first scenario, the area whose load power demand fluctuates is relatively close to the area where the two measurement nodes are located. Some preliminary tests were done and it was concluded that a 10 MW increase/decrease in the load power demand will be done every 0.33 s for 5 s. Before the first fluctuation is applied the system will run for 1 s in steady-state and after the last fluctuation is applied the system will run until 7 s has passed.

In the second scenario, an area that is located further away will experience fluctuations in load power demand. Preliminary tests were also completed here and hence a 10 MW change in load power demand will be applied every 0.5 s for 5 seconds. The other conditions will be kept the same and the system will be reset back to steady-state between the scenarios. 10 MW is used to check if even very small forced oscillations comply with the theory and to see if similar resonance effects as those presented in [34] can be observed.

6.2 Results Case Study

The resulting frequency graph from scenario 1 can be seen in Figure 6.1. The red solid line is the resulting oscillation on a bus located in the area where the load power demand was regulated. As can be seen in the figure the frequency does not vary by more than ±0.00007 Hz from the equilibrium of 50 Hz. The presence of a forced oscillation can be observed between 1.0 s and 5.0 s and after this, the oscillation is damped out.

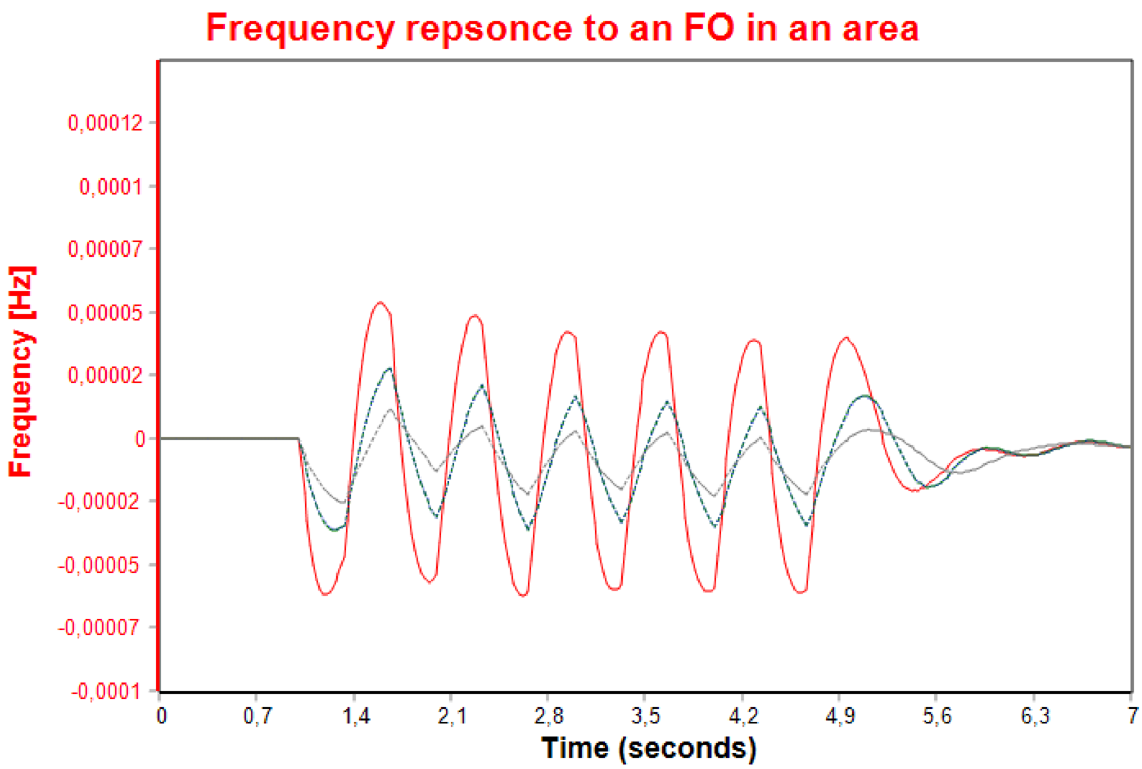

Figure 6.1: Frequency plot from scenario 1. The frequency variations in the area where the load power is changed (red solid line) clearly has a larger amplitude than the two nodes in the measurement area (green and blue) and the area furthest away (gray dotted line).

Figure 6.2 shows the results from scenario 2, where the forced oscillation was created in an area further away from the base nodes. Also in this scenario, the frequency only varied by a max of ±0.00007 Hz from the equilibrium at 50 Hz. As with scenario 1, the forced oscillation can be observed in the graph between 1.0 s and 5.0 s and then being damped out by the system as expected.

From Figure 6.1 and 6.2 it seems that the oscillations are damped out fairly quickly and the frequency is expected to continue oscillating at 7 seconds but return to equilibrium at 50 Hz soon after. Discussions around the case study can be found in Chapter 8.2.

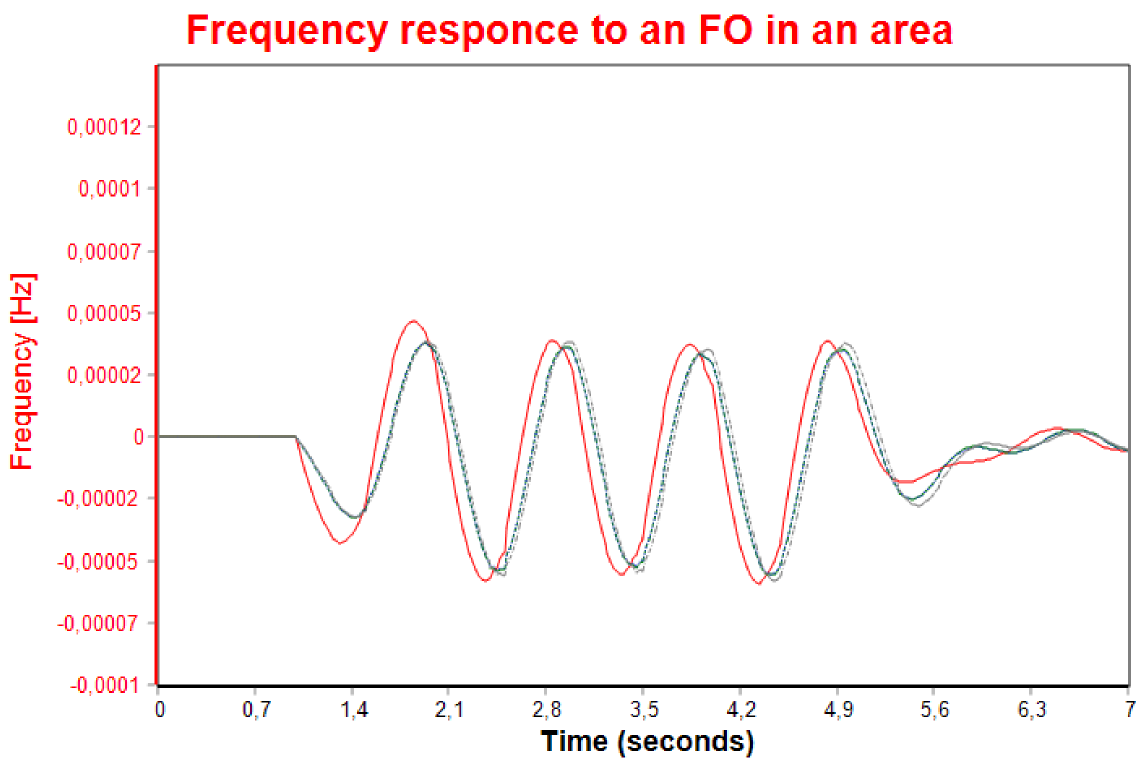

Figure 6.2: Frequency plot from scenario 2. The frequency variations in the area with load power fluctuations (red) is again slightly larger in amplitude, but here it is not as adamant.

7. Results from Literature Search

As stated at the end of Chapter 5 it is imperative to not only detect the presence of FOs in the system but also be able to locate their sources so the fault can be fixed as fast as possible. Ways of achieving both of these central concepts will be presented through existing literature on the subjects. First, an algorithm designed to discover the presence of FOs in a power system and distinguish them from electromechanical modes is presented. This algorithm is showing great results on both simulated and real-world data. Sequentially a method for locating the source of the FOs is presented. The method can in some cases be used to build on the detection algorithm, such that faults can be cleared quickly. This method has only been tested on simulated data but was able to locate the exact source or the area where the source lies 100% of the time.

7.1 Detecting Forced Oscillations

The detection of FOs in power systems can become very difficult when considering increasingly complex power systems. Follum and Pierre have in [35] suggested a method where calculated periodograms of synchrophasor measurements (from PMUs) are compared to a detection threshold. From the comparison FOs are detected and their frequencies are estimated. This detection algorithm can outperform many classical detection methods as it takes into account the colored nature of real PMU data, in contrast to simulating with white Gaussian noise, which is done by others. White Gaussian noise has a constant power spectral density (PSD) for all frequencies, while in a real power system the ambient noise will be colored, meaning the shape of the PSD will depend on the system´s dynamics [35]. The colored nature is taken into account by having the detection threshold vary with frequency. The detection algorithm proposed was tested on both simulated data to ensure its usefulness, and then implemented on real-world historical data to test the effectiveness of the algorithms in practical situations.

The main idea of the process is rather straightforward, a forced oscillation is detected at frequencies where the periodogram of some measured data exceeds a set threshold. The exact steps of how this is achieved will be explained briefly in this thesis and can be read in detail in [35] and the references therein. One of the main ideas behind the algorithm is having a threshold that is reliant on the probabilities of detection and false alarm. Respectively this is the probability of detecting an FO when there is one present and the probability of detecting an FO when there is none. This process is highly theoretical and starts with a hypothesis test where the null hypothesis is the lack of an FO present and the alternative hypothesis observes the presence of an FO. This can be shown using

$$\begin{aligned} H_0 &: y(k) = x(k), & 0 \le k \le K-1 \\ H_1 &: y(k) = x(k) + s(k), & 0 \le k \le K-1, \end{aligned} \tag{7.1}$$

where y(k) is the measurement from a PMU, x(k) is the ambient noise and s(k) accounts for the presence of a forced oscillation.

To choose between H_0 and H_1 the periodogram, $\hat{\phi}_y(\Omega_B)$, will serve as the test statistic and will be compared to a threshold $\gamma(\Omega_B)$. Ω_B is the set of B frequencies, which is an arbitrary set of frequencies that will be checked for FOs.

An FO will not be detected if

$$\hat{\phi}_y(\omega_m) < \gamma(\omega_m) \text{ for all } \omega_m \in \Omega_B. \tag{7.2}$$

Similarly if

$$\hat{\phi}_y(\omega_m) \ge \gamma(\omega_m) \text{ for } \omega_m \in \Omega_B, \tag{7.3}$$

then a FO is detected with the initial frequency estimate ω_m. The detection threshold will be related to the probability of the periodogram exceeding this threshold when H_0 is true, and from there, an expression for $\gamma(\Omega_B)$ will be formed. This probability is the probability of false alarms (P_{FA}) and can be expressed as

$$P_{FA} = P(\hat{\phi}_y(\omega_m^{max}) > \gamma(\omega_m^{max}); H_0). \tag{7.4}$$

This can be further rearranged and manipulated to finally solve for an expression for the detection threshold (7.5). It is extended to include all frequencies in Ω_B.

$$\gamma(\Omega_B) = -\phi_x(\Omega_B) \ln\left(\frac{1}{B} P_{FA}^{max}\right), \tag{7.5}$$

where ϕ_x is the PSD of the ambient response and P_{FA}^{max} is the maximum allowed value for P_{FA}. By making the detection threshold proportional to ϕ_x in this expression the algorithm can account for modal oscillation in the data, which means it should be able to distinguish well between FOs and the electromechanical modes of the system. P_{FA}^{max} is often considered a user-defined input and can depend on the context the algorithm is used in. A large P_{FA}^{max} is used when also small FOs are of interest, but this takes longer to compute. Choosing a smaller P_{FA}^{max} will only detect forced oscillations with a certain amplitude, which can be more suited for online testing. The probability of detection can be calculated from P_{FA}^{max} and if this value is acceptable then the detection threshold can be calculated using (7.5).

Another metric in the algorithm that ensures great accuracy is the usage of several detection segments, each with various lengths. This allows the test to detect large FOs very fast and at the same time reliably detect even very small FOs that might not be visible in time-domain data. When choosing the smallest and largest segments, the signals under analysis and their application must be taken into account, hence a certain amount of knowledge of the system is required to obtain good results. With the use of several detection segments, this detection algorithm produces several detected frequencies for each sinusoid, some being redundant. To solve this a leakage filter is applied and then generally the detection that comes from a larger detection segment is chosen, disregarding the others.

Follum and Pierre tested their algorithm on both simulated data, generated at 120 samples per second using the miniWECC model (described in [36]) and field measured data. The FO's frequency was set equal to one of the electromechanical modes in the model to consider an extreme case. In the first simulation an FO with $A^2/2\phi_x(\omega_m^{FO}) = 0.1$ was considered and in the second simulation an FO with $A^2/2\phi_x(\omega_m^{FO}) = 0.001$ was used. In both cases, the FO was detected very accurately and the total time taken to perform the detection over the 400 trails (200 for each simulation) was 0.2004 s. This indicates that this algorithm can be used in real-time calculations. The algorithm was also tested on real PMU data where it accurately detected an FO with a known source, but also found another FO that up until that time was unknown. The results from the simulated and real-world case showed that it is well suited to both quickly detect large FOs, while also reliably detecting smaller FOs.

The algorithm presented shows a lot of promise to become a well-functioning resource for system operators trying to detect FOs that are occurring in the power grid. The simulation results also provided great detection times, showing that it can be implemented in a real-time operating scenario. But in contrast, no time-scale was provided when the algorithm was used on real measured data, so it begs to question if the same time-scale was upheld or if it will struggle when put in a real system. The simulated miniWECC model equivalences many large generating areas into single generators and only uses transmission lines with a rating of at least 230 kV and a certain length. Based on these constraints further research must be done testing the performance of the algorithm on larger and more complex systems. It is stated that this is the next process forward for the people working with the algorithm. The results from this further testing should also be taken into account before the algorithm can be implemented into a real operating system [35].

There is also a question raised by the authors on the PSD estimate used in calculating the detection threshold. It is stated that if real-time estimates are used then possible new electromechanical modes occurring in the system will not sound alarms for these modes. If seasonal estimates are used then a new mode will sound alarms as the new modes have not been accounted for, but then further research needs to be done to establish if it is a forced oscillation or modal oscillation. If the algorithm is included as a supplementary tool to traditional oscillation detection tools, then real-time estimates can be used. The algorithm will then focus on FOs and the traditional detection tools will detect general electromechanical modes.

The focus of the explored algorithm is to detect FOs, and thus it is not able to locate the source of the FO. As stated earlier FOs are not part of the system itself but come from faulty equipment which needs to be fixed. A large FO detected in one part of the system may have its origin in a completely different place due to resonance effects. In such cases, operators with great knowledge of the system are needed or an additional technology for the location of the source is needed, such that the faulty equipment can be fixed and the FO can be negated.

7.2 Locating the Source of Forced Oscillations

To fix the faltering equipment or negate the stable limit cycles inducing FOs in the power system their source has to be located. This is an area where technology has not yet come far enough to be properly implemented into system operations. Most of the current research and results come from simulations on models created from the real world, without much testing on real power system mechanics. The method for locating the source of FOs presented by the researchers in [37] also falls into this category. The results should therefore be critically interpreted and one can not assume to observe the same level of accuracy if used in real-time operation, however, the results are very promising.

It is stated by the researchers that the focus will be on forced oscillations that have a frequency in the range of the electromechanical modes of the system, which usually have frequencies up to 2 Hz [37]. This is because FOs with frequencies higher than this usually have their largest amplitude closest to the source and are hence relatively easy to locate [34]. It can in many cases be significantly harder to locate the source of FOs when their frequency is in the range of system modes due to resonance effects explained before. The algorithm proposed by Agrawal et al. uses information about the system to be studied, together with measurements recorded by PMUs, and was simulated and validated on the miniWECC model (see [36] for an overview).

The method will inject a periodic disturbance (simulating a forced oscillation) to one or more of the inputs, generators in this instance, and the measurements will be recorded by PMUs at certain locations. This is illustrated in Figure 7.1. The measurements recorded by the PMUs can be modeled in the frequency domain by

$$\mathbf{Y}(\omega_0) = \mathbf{H}(\omega_0)X(\omega_0) + \mathbf{N}(\omega_0), \tag{7.6}$$

where $\mathbf{Y}(\omega_0)$ contains the Discrete Fourier Transformations (DFTs) of the measured PMU data, $\mathbf{H}(\omega_0)$ are the transfer functions from the source generator to each of the outputs. $X(\omega_0)$ is the DFT of the forced input and $\mathbf{N}(\omega_0)$ holds DFTs of the ambient noise. $\mathbf{Y}$, $\mathbf{H}$ and $\mathbf{N}$ are column vectors and ω_0 is the frequency of the FOs with units $[\frac{\text{rad}}{\text{s}}]$.

The main principle of this method is to run through the system making each generator the source of the FO. Then for each run, a normalized error will be calculated and stored. After each generator has been assumed to be the source the errors are compared and the case with the smallest normalized error will be the chosen estimate for the source of the FO. As can be seen in Figure 7.1 the system has N amount of generators and M PMU measurement locations. Given index i going from 1 to N, the transfer function of generator i is given by

$$\mathbf{H}_i = [H_{i1}\ H_{i2}\ \cdots\ H_{iM}]^T, \quad i = 1, 2, ..., N. \tag{7.7}$$

The forced input with fundamental frequency, ω_0, can be given by the Fourier series

$$x(t) = \sum_{k=-\infty}^{\infty} X_k e^{jk\omega_0 t}, \tag{7.8}$$

which is complex and $j = \sqrt{-1}$. $X_k = X(k\omega_0) = |X_k|e^{j\angle X_k}$ represents the k^{th} harmonic component of the input, giving that $X_0 = 0$ and $X_k = X^*_{-k}$ for $k = 1, 2, ..., \infty$. The column vector for the measured PMU data converted with the DFT is given by

$$\mathbf{Y}(\omega_0) = [Y_1(\omega_0)\ Y_2(\omega_0)\ \cdots\ Y_M(\omega_0)]^T. \tag{7.9}$$

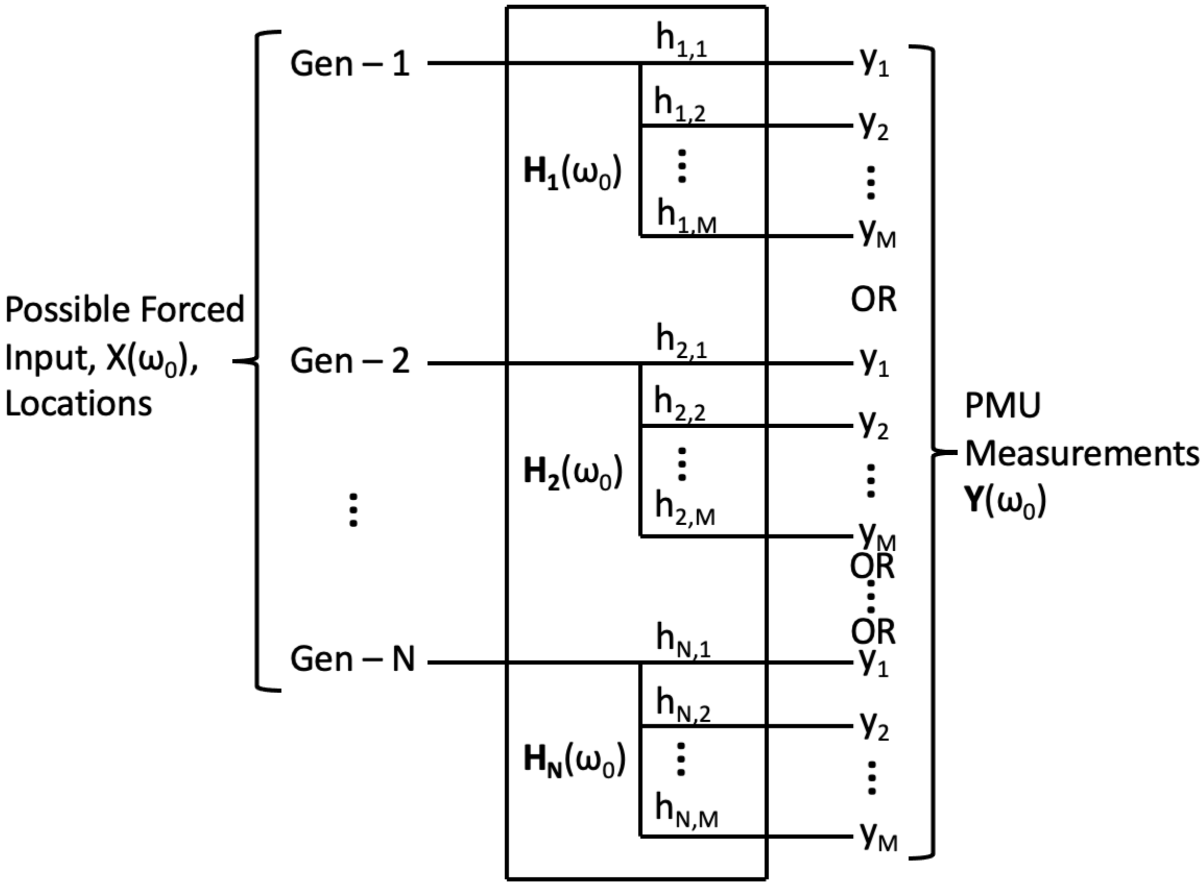

Figure 7.1: Illustration of the relationship between a forced input and PMU measurements through a transfer function (similar to G in (5.9)) in frequency domain. Inspiration for the illustration gathered from [37].

If generator i is assumed to be the source of the forced oscillation then (7.6) can be rewritten as

$$\mathbf{Y}(\omega_0) = \mathbf{H}_i(\omega_0)X_i(\omega_0) + \mathbf{N}(\omega_0), \tag{7.10}$$

using the above definitions. As stated before $\mathbf{Y}(\omega_0)$ are the DFTs of the PMU measurements and $\mathbf{H}_i(\omega_0)$ is gathered from the system information. The forced input, $X_i(\omega_0)$, is unknown and needs to be estimated. This can be done by solving (7.10) using the linear least-squares method, giving the estimate to be calculated by

$$\hat{X}_i(\omega_0) = (\mathbf{H}_i(\omega_0)^T\mathbf{H}_i(\omega_0))^{-1}\mathbf{H}_i(\omega_0)^T\mathbf{Y}(\omega_0). \tag{7.11}$$

Using (7.11) gives an estimate of the forced input when considering generator i as the source of the FO. Running this through the system for every generator will result in N amount of estimated forced inputs. Then the normalized error for each of the resulting estimates must be calculated to conclude which gives the closest output. This is calculated using

$$\epsilon(i) = \frac{\|\mathbf{Y}(\omega_0) - \mathbf{H}_i(\omega_0)\hat{X}_i(\omega_0)\|}{\|\mathbf{Y}(\omega_0)\|}. \tag{7.12}$$

The forced input estimate which gives an output that is closest to the measured one will have the smallest error (ϵ). This is fairly intuitive, but further explanation and illustration of this fact can be found in [37]. If the system was completely noiseless then the error would be equal to zero when simulating the correct generator as the input, but as a power system always contain some ambient noise due to small random load changes the estimate giving the smallest error is perceived as the most reliable estimate.

Agrawal et al. state that the method can encounter some difficulties locating the exact source if two generators have very similar transfer functions. As can be seen, formula (7.11) is highly dependent on the transfer function of the generator that is being checked as a possible source. Hence the estimate of two generators with similar $\mathbf{H}(\omega_0)$ will have very similar errors and it might be impossible to correctly decide which is the actual source. This can happen in one out of two cases. Either the two generators are running in parallel or they are located very close to each other. If this is true the transfer functions can align when only looking at high voltage buses as the measurement locations. This is also slightly dependent on the configurations and characteristics of the generators connected to the same bus. In this situation, the method can locate the area well, but possibly not the generator in that area. The second situation is much rarer but can happen. If the FO has the same frequency as an electromechanical mode that is critically damped then the transfer functions of two generators might align. The details behind this can be found in Agrawal [37], but will not be covered further here.

As mentioned before the method was tested using simulations in the miniWECC model. Power system toolbox was used to obtain state-space matrices and from them the transfer functions were calculated, more details of which are available in [37]. The output vector $\mathbf{Y}(\omega_0)$ was calculated using DFT of voltage magnitude measurements at the high voltage buses connected to the generators. Measurements were taken at a sampling rate of 30 samples per second for one minute, where the forced oscillation was present during the whole sampling time. For the input, a single sinusoid with amplitude equal to 1% of the source generators rating was chosen and the normalized error was calculated using (7.11) and (7.12). 1000 Monte-Carlo trails were used where the random quantity was the load variations in the system.

Agrawal et al. displayed four situations, one where the FO"s frequency was outside the range of the inter-area modes of the system, two cases where the FO has the same frequency as one of the modes, where one of the times the mode was critically damped and a forth where the FO's frequency was close, but not equal, to that of a critically damped mode. In each of these four cases, the method was able to predict the exact source or the correct area containing the source with 100% accuracy. This means that from an operator's point of view they will always know where to look for the error. Either they know the exact generator or the correct area. Discussions regarding this article will be found in Chapter 8.4.

8. Discussion

8.1 Literature Selection and PMUs

As mentioned in Chapter 4.1 forced oscillations is an area where there currently is not a vast amount of literature, especially for detection algorithms and source location methods. This is because oscillations in power systems is a relatively new area of research. As a result, many researchers have focused on different methods and there is little overlap. Hence finding methods or algorithms which are backed up by more than one article was difficult. This is unfortunate because the solutions have most likely not been tested on other power systems than the ones in the articles. In addition, the methods explored in this thesis ([35], [37]) have not been critically evaluated by unbiased actors. Such actors can more easily see the shortcomings of the methods, providing a wealth of insight.

In a conversation with a system operator at Statnett, it was discovered that although there is a decent amount of PMUs installed in the Nordic power system most of these are currently used for research and post contingency analysis [22]. This is likely to change following the installment of more PMUs and discoveries made during the NEWEPS project (and other projects between the Nordic TSOs such as the Impala project). More PMUs will give greater coverage of synchronized data at high sample rates. When there are not enough PMUs they might not cover the system well enough and hence it's better to use the traditional SCADA system, albeit receiving lower quality data. The user interface for PMU data will be improved during the NEWEPS project and further research and discussions around this can be found in [38].

Having a power system that is creating several times more measurements and is getting more and more automated also brings along new challenges. There will for example be questions about how long data should be stored before it is deleted and where all this new data should be stored if the system is not currently ready for such an increase. There will also be a question about cybersecurity when everything is getting more digitized. More cyberattacks are likely to be expected and systems preparing and protecting against this should be implemented. This is however outside the scope of this thesis and will not be discussed further.

8.2 Case Study Discussion

In both scenario 1 and 2, it could be seen from the graphs that the frequency oscillations did not vary with more than ±0.0001 Hz. Such small oscillations would not be visible in typical PMU data, which proves system operators require helping tools to detect all FOs that may be present in a system. It was checked to see if the small oscillations were due to the very small change in load power demand. For scenario 1 the 10 MW change only constituted a 1.85% variation, the original value was 550 MW. For scenario 2 the change accounts for a 2.27% with an original value of 440 MW. Runs were done where this change was increased, however, significantly larger oscillations were not observed, and with the desired effect being visible with the 10 MW variation this was kept as is.

The theory states that FOs which do not resonate with electromechanical modes in the power system should have larger amplitudes at the area where they are located. Following on it is expected that the further away from the source area an observation is taken, the smaller the amplitude should be. In scenario 1 this was visible in the frequency plot. The amplitude is largest in the area where the FO comes from, then it becomes smaller the further away from the source measurements are taken. On the contrary scenario 2 is interesting. Here the same buses are measured, but instead of imposing the change every 0.33 s, it was imposed every 0.5 s. Surprisingly in Figure 6.2 the amplitudes of all the four measurement buses are practically the same. This could imply that the frequency of this FO is closer to an electromechanical mode and some resonance effects are present in the test system. This unpredictable effect is something that should be researched and tested further for this system.

A shortcoming of PSS/E is that it is unable to directly show the power fluctuations of a bus in the system. Only Frequency, Voltage, and Voltage + angle are options to observe. Hence it was not possible to directly see how the power in the measurement buses changed. This could have given some further insight into possible resonance effects in scenario 2 as discussed above. Quite intuitively if the frequency amplitudes are equal and this would impose similar percentage changes in power fluctuations, then it can be expected that in the measurement area the buses will experience larger power changes due to a larger starting load power demand (550 MW vs 440 MW).

8.3 Detection Algorithm

As has already been briefly discussed in Chapter 7.1 the detection algorithm considered in this thesis has only been tested on the miniWECC model, where many simplifications have been made. In the interest of the NEWEPS project, the algorithm proposed must also be tested in the Nordic power system. Perhaps firstly on a simplified model of this system, but before a proper prototype can be developed a full system model test should also be completed. Furthermore, the authors of [35] stated that the future work will be on historical data, with no mention of real-time online testing [35]. This is something to be considered by the benefactors of the NEWEPS project, as the algorithm might not work in system operations, but is best suited for post-contingency analysis done by analysts and not system operators. At the time of writing it was expressed by a system operator at Statnett that knowing whether an oscillation is forced or transient is at the time of writing not of great interest for them. However if the algorithm can be made suitable for online operations, system operators can use the information provided to make decisions better suited for forced versus transient oscillations [22].

At the current development of the detection algorithm presented in [35] and integration of PMUs in the Nordic power system, it is reasonable to believe that the algorithm is too complex to be used for online operations at the time of writing. High complexity in proper implementation of the algorithm comes from the need for significant system knowledge by the operators. Due to this, the algorithm will take time to start for each contingency, and system operators will therefore restrain from utilizing it for online monitoring and control. This is something that was also seen in early-stage PMU-data implementation [22]. Through the work done in the NEWEPS project and increased incorporation of more PMUs in the Nordic power system, the significant system knowledge needed can be gathered and stored in other ways. With the use of for example machine learning the relevant system information and parameters can be gathered without the need for system operator inputs (more on machine learning can be found in [39]), reducing the complexity of the algorithm in [35]. System operators can henceforth much easier utilize the detection algorithm in [35] in an online setting. The author of this thesis, therefore, believes that with increased research and development from the NEWEPS project this detection algorithm can become an integral part of the future monitor and control system.

The detection algorithm presented in [35], checking different frequencies against a threshold, has only been tested on periodic FOs. There are other detection algorithms, such as energy detectors (found in [40]), that can work better when the FO has time-varying frequencies because they examine a range of different frequencies [35]. However, it is stated in [35] that their detection algorithm has a distinct advantage over other detection methods because it is easily able to account for electromechanical modes and distinguish between them and FOs. It can also account for the colored nature of ambient noise. Based on this the author of this thesis's belief that the algorithm presented in [35] is a great starting point when creating a prototype for the NEWEPS project is upheld. Further down the line other detection algorithms can be incorporated, however much testing is needed to check if this is feasible.

At the time of writing, several different detection algorithms are being developed and tested, each one utilizing a different approach. Many of them have been studied and compared in [32]. Most of the algorithms regarding the detection of FOs have at most been tested on historical real-world data and can hence be given a TRL of 3 or 4 on the Statnett scale presented in Figure 4.1. The algorithm discussed in this thesis can perhaps even be given level 5 as it has been validated in a relevant environment, but no prototype has been properly made, and thus it is placed in TRL 4.

8.4 Localization Method

Although this method is showing great results in the article by Agrawal et al. it only displayed four of the tests that were done without mentioning the results for the rest. It is unclear if this is because the chosen four were the most difficult cases and hence showed how well the method performs in very tough situations. As it is only on simulated data it could be useful to see the results from more than just the one system mode because one would not only consider one mode in a real-world system. Another aspect of only using simulations is that there is no knowledge about the goodness of the method on real measured data. This further implies that the real-world application of the method can be questioned and this is an area that needs to be researched more before this method can be implemented into an operating central.

Another reason why further research is needed where real-world data is used is that as with the previously discussed detection algorithm, the miniWECC model was used. Emphasis is made that this is a reduced model of the much larger and more detailed western North American Power System (wNAPS). In miniWECC many generators have been equivalenced into one generating unit and only transmission lines of a certain length and voltage area used [36]. If the method were used on the larger wNAPS model then there might be more cases when it only was able to locate an area where the FO is coming from instead of exact generators. Although there is still much testing needed before this method can be implemented into a system's operating central, the researchers state that it is very suitable for online applications due to its simplicity and therefore computationally effectiveness [37].

Further shortcomings for the purposed method are that it requires prior knowledge of the frequency of the forced oscillation it is trying to locate the source of. This means that even if it was made ready to be implemented into power system operations its effectiveness is dependent on the effectiveness of a detection algorithm. Having an algorithm that is always dependent on another one can be problematic. When it potentially gives out incorrect locations, it can be unclear if the fault lies in the detection algorithm or the localization method.

In Agrawal et al.´s proposed method the simulations were run such that the FO was present during the whole sampling time. This design choice is not explained and is something to critically examine as it will give a very high signal-to-noise ratio (SNR). The detailed calculations made in [35] show that having a high SNR often gives better simulation results when examining FOs because the FO is visible in the data. This is supported in [32], where it is communicated that it is often the case in real-world data that FOs have a small SNR.

[32] gives further insight into many other possible solutions for locating the source of FOs in power systems. As a general trend, it seems many of the ones presented here are good at locating certain FOs but struggle to be general enough to cover all. Four scenarios are highlighted as key aspects a good location method should cover:

- FOs with different frequency ranges (i.e. 0.12 Hz to 14 Hz)
- FOs in a large and complex system
- FOs with low SNRs
- FOs imposed by different causes.

Although it is not included in [32], the proposed method in [37] also fails to address some of these scenarios for the tests presented in the article. However, with the method being so computationally simplistic and scoring a 100% accuracy for the tested cases it is worth testing it for more scenarios and on a more complete Nordic power system. FO source locating methods can be argued to have reached a TRL 4 in some cases, but generally, they achieve level 2-3 as tests have only been done on simulated cases with no real-world data implemented. This further implies that much testing and work is yet to be done to reach the desired TRL 5-7 for the NEWEPS project.

9. Conclusion and Future Work

9.1 Conclusions

This master's thesis set out to study the question: ”To what extent can Forced Oscillations be monitored and controlled in a modern power system, using PMUs?”, and in doing so further sub-questions were explored. The thesis is a work in collaboration with Statnett SF and the NEWEPS project they are part of, hence its focus was on the Nordic power system. A case study and literature search was completed.

In the case study, the author inspected if FOs have larger amplitudes in the area where they are imposed as the theory would suggest. In scenario 1 the system performed as expected. The amplitudes of oscillations in a frequency versus time graph decreased as the measured buses got further away from the source. Surprisingly in scenario 2, the amplitudes in the same graph were close to equal, which can indicate the presence of resonance effects. In this scenario detection algorithms and localization methods would be needed to understand the system well.

After one of the characteristics of FOs was explored through the case, a second literature study was performed to answer the sub-topics and use the acquired knowledge to answer the overall research question. During the literature study, one method for detecting FOs and one method for locating their source was found. These are focus areas in WP5 of for NEWEPS project and were investigated further.

The method used for detecting forced oscillations in a power system calculates a threshold based on a scaled version of the PSD of the ambient noise component. Then the periodogram of measured PMU data is compared to this threshold and if the threshold is exceeded then a forced oscillation is detected with the natural frequency equal to the frequency that is being tested for. The algorithm also includes the use of multiple detection segments and user defined windowing, which means the algorithm can quickly detect large FOs and accurately detect small ones. Follum and Pierre performed testing using simulations on the miniWECC model and real-world PMU data. In the authors' simulations, the algorithm performed perfectly and very fast. When they tested on real

PMU data one FO, which had already been located by system operators were detected accurately. Surprisingly the algorithm also detected a previously unknown FO, showing the effectiveness of the algorithm.

Detecting forced oscillations is a good starting point for being able to successfully monitor them, however, they can not be controlled and must be removed. Because their source is often faulty equipment, this equipment has to be located in the system so it can be fixed. Such a localization method was also investigated in the literature study. The authors present a method where every generating unit in the power system is in turn set as the source. Then simulated output PMU data is generated based on this assumption. This data is then checked against real PMU measurements and the run with the smallest error will reveal the source generating unit. In the article, the method was only tested on simulated data and in the four presented cases it was able to identify the correct generating unit or its immediate area with 100% accuracy. As it is not a very complex method mathematically it is stated that it will work well in real-time applications, but it requires prior knowledge of the FOs frequency, and their claim has not been tested using real-world data.

Regarding the main research question, this thesis presents two methods that will help monitor and control FOs in a modern power system. The current system operations in the Nordic power system do not regard FOs during online operation. However, it is becoming increasingly clear that FOs should be monitored in real-time to take correct counter-actions to contingencies. With the increased implementation of PMU-data in online system operations the process of detecting and locating FOs in complex systems is becoming possible.

Through a case study and a literature review, this thesis contributes to the NEWEPS project, by presenting two methods to be further researched. These show great capabilities of working together, whilst also providing system operators with a wealth of fast and reliable information. As previously stated, much of the current literature recognize the need for both detecting FOs as well as locating their source, but only considers one of them. On the other hand, this thesis stresses that one will not be effective without the other, and to accurately monitor and control FOs in a modern power system a combined method or both have to be implemented.

9.2 Future Work

This master thesis is situated at the very starting phase of the NEWEPS project and is consequently an introductory research looking at WP5. Further work in the WP will be done by TSOs, research institutions, or Ph.D. students in one or more of the Nordic countries. Due to this, some suggestions of future work in this WP is presented below:

- The methods that have been presented in this thesis have been tested on simulated data or real PMU data from the North American power system. To validate the performance of the methods, they should be tested on more PMU data or test systems from the Nordic power system.
- Currently most research is focused on one aspect of forced oscillations. Therefore research should be done exploring whether or not the detection algorithm and localization method can be combined.
- Further research should also be done on the performance of the methods presented in this thesis regarding different scenarios that can come forth with forced oscillations. Four of these were introduced in Chapter 8.4.

References

[1] G. Feller, *Renewable Energy's Impact on Power Systems*, 2019, [Online]. Available: https://www.tdworld.com/renewables/article/20973433/renewable-energys-impact-on-power-systems (visited on 05/04/2021).

[2] E. T. Commission, Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, *Energy Transitions Commission*, 2018, [Online]. Available: https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC_MissionPossible_FullReport.pdf.

[3] S. Twidale, *Renewables overtook fossil fuels in EU electricity mix in 2020: Report*, 2021, [Online]. Available: https://www.reuters.com/article/us-eu-renewables-idUSKBN29T0T8 (visited on 05/04/2021).

[4] European Commission, The European Green Deal, *European Commission*, vol. 53 (9): 24, 2019, DOI: 10.1017/CBO9781107415324.004.

[5] X. Kong, Y. Chen, T. Xu, C. Wang, C. Yong, P. Li, and L. Yu, A hybrid state estimator based on SCADA and PMU measurements for medium voltage distribution system, *Applied Sciences (Switzerland)*, vol. 8 (9), 2018, DOI: 10.3390/app8091527.

[6] K. Uhlen, P. Overholt, and O. Valentine, Synchrophasor applications for wide area monitoring and control, *ISGAN annex*, 2016, [Online]. Available: https://www.iea-isgan.org/wp-content/uploads/2018/02/ISGAN_DiscussionPaper_SynchrophasorApplications_2016-1.pdf.

[7] J. Follum, Power System Oscillatory Behaviors, (May), 2017, [Online]. Available: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26375.pdf.

[8] Neweps, Statnett, Sintef, and NTNU, NEWEPS – Nordic Early Warning Early Prevention System, (February), 2021.

[9] A. Rabiee, A. Keane, and A. Soroudi, Green hydrogen: A new flexibility source for security constrained scheduling of power systems with renewable energies, *International Journal of Hydrogen Energy*, (xxxx), 2021, DOI: 10.1016/j.ijhydene.2021.03.080.

[10] ENTSO-E, *ENTSO-E releases pan-European network development plan for the next decade and beyond*, 2020, [Online]. Available: https://www.entsoe.eu/news/2020/11/06/entso-e-releases-pan-european-network-development-plan-for-the-next-decade-and-beyond/ (visited on 02/11/2021).

[11] ENTSO-E, TYNDP 2020 Highlights, 2020.

[12] Nordic TSOs, Challenges and Opportunities for the Nordic Power System: 66, 2016, [Online]. Available: https://www.fingrid.fi/globalassets/dokumentit/fi/yhtio/tki-toiminta/report-challenges-and-opportunities-for-the-nordic-power-system.pdf.

[13] Statnett, *Nordisk Kraftflyt*, 2021, [Online]. Available: https://www.statnett.no/for-aktorer-i-kraftbransjen/tall-og-data-fra-kraftsystemet/ (visited on 02/12/2021).

[14] Fingrid, Statnett, Energinet, and S. Kraftnät, Nordic Grid Development Perspective 2021, 2021, [Online]. Available: https://www.epressi.com/media/userfiles/107305/1613133858/ngdp2021-webinar-materials-1.pdf.

[15] S. M. Berlijn, *FYS377 Kraftsystemets rolle*, Ås, 2020.

[16] ENTSO-E, Research, Development & Innovation Roadmap 2020 – 2030: 32, 2020, [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/RDC%20publications/entso-e-rdi_roadmap-2020-2030.pdf.

[17] Statnett, Fingrid, S. Kraftnät, and Energinet, Nordic Early Warning Early Prevention System (NEWEPS), (March): 1–13, 2020.

[18] H. Bentarzi, M. Tsebia, and A. Abdelmoumene, PMU based SCADA enhancement in smart power grid, *Proceedings - 2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering, CPE-POWERENG 2018*: 1–6, 2018, DOI: 10.1109/CPE.2018.8372580.

[19] NASPI, Synchrophasor Technology Fact Sheet: 1–4, 2014, [Online]. Available: https://www.naspi.org/sites/default/files/reference_documents/33.pdf?fileID=1326.

[20] A. G. Phadke and T. Bi, Phasor measurement units, WAMS, and their applications in protection and control of power systems, *Journal of Modern Power Systems and Clean Energy*, vol. 6 (4): 619–629, 2018, DOI: 10.1007/s40565-018-0423-3.

[21] O. Finseth, *Questions about PMU*, Oslo, 2021.

[22] G. Sætermo, *Personal conversation*, Oslo, 2021.

[23] J. D. Glover, T. J. Overbye, and M. S. Sarma, *Power System Analysis & Design*, Sixth Edit. Cengage Learning, 2016: 941.

[24] H. S. Nygård, *FYS377 -Digitale elektriske kraftsystemer Kapittel 1 - Introduksjon*, Ås, 2020.

[25] Statnett, *TABELL TRL: Technology Readiness Level*, Oslo, 2020.

[26] ENTSO-E, *ENTSO-E Transmission System Map*, 2019, [Online]. Available: https://www.entsoe.eu/data/map/ (visited on 04/26/2021).

[27] M. Særen and M. Giset, Systemjording, (august), 2017.

[28] Siemens Industry Inc., "Program Operation Manual - PSS®E 34.6.1," Tech. Rep., 2019.

[29] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cursem, and V. Vittal, Definition and classification of power system stability, *IEEE Transactions on Power Systems*, vol. 19 (3): 1387–1401, 2004, DOI: 10.1109/TPWRS.2004.825981.

[30] Statnett, Rapport fra Systemansvarlig, 2018.

[31] K. Prasertwong, N. Mithulananthan, and D. Thakur, Understanding low-frequency oscillation in power systems, *International Journal of Electrical Engineering Education*, vol. 47 (3): 248–262, 2010, DOI: 10.7227/IJEEE.47.3.2.

[32] M. Ghorbaniparvar, Survey on forced oscillations in power system, *Journal of Modern Power Systems and Clean Energy*, vol. 5 (5): 671–682, 2017, DOI: 10.1007/s40565-017-0273-4.

[33] E. W. Kamen and B. S. Heck, *Fundamentals of Signals and Systems using the Web and MATLAB*, 3rd. Pearson, 2014: 1–649.

[34] S. A. N. Sarmadi and V. Venkatasubramanian, Inter-area resonance in power systems from forced oscillations, *IEEE Transactions on Power Systems*, vol. 31 (1): 378–386, 2016, DOI: 10.1109/TPWRS.2015.2400133.

[35] J. Follum and J. W. Pierre, Detection of Periodic Forced Oscillations in Power Systems, *IEEE TRANSACTIONS ON POWER SYSTEMS*, vol. 31 (3): 2423–2433, 2015, DOI: 10.1109/TPWRS.2015.2456919.

[36] D. Trudnowski, D. Kosterev, and J. Undrill, PDCI damping control analysis for the western North American power system, *IEEE Power and Energy Society General Meeting*: 13–15, 2013, DOI: 10.1109/PESMG.2013.6672718.

[37] U. Agrawal, J. W. Pierre, J. Follum, D. Duan, D. Trudnowski, and M. Donnelly, Locating the source of forced oscillations using PMU measurements and system model information., *IEEE Power and Energy Society General Meeting*, vol. 2018-Janua: 1–5, 2018, DOI: 10.1109/PESGM.2017.8273770.

[38] E. Bera Mathiesen, *Situational awareness in the power system control rom of the future - a NEWEPS project*, Ås, 2021.

[39] T. Korten, *A Study of Machine Learning Methods Used as Decision Support Tool for Grid Operators - The NEWEPS Project*, Ås, 2021.

[40] M. Donnelly, D. Trudnowski, J. Colwell, J. Pierre, and L. Dosiek, RMS-energy filter design for real-time oscillation detection., *IEEE Power and Energy Society General Meeting*, vol. 2015-Septe: 1–5, 2015, DOI: 10.1109/PESGM.2015.7286192.

Appendix A. TRLs Explained.

Table A.1: TRLs explained more in depth. The table is adjusted from a Norwegian version supplied from Statnett.

TRL-level		Technology description
1	**Basic principles observed**	The main principles for the technology are studied through literature studies. A possible idea is then formed that is based on the principles which are identified.
2	**Technology concept formulated**	A practical application is formulated, which embodies the system limits. The base components necessary for the concept are identified.
3	**Experimental proof of concept**	Active work, experiments in labs and analytical studies, is begun to validate separate elements of the technology. Physical principles and expected characteristics are confirmed.
4	**Technology validation in lab**	Components are integrated in a test version to confirm their compatibility. The base functionality of the components and system are tested in labs or simulated to further develop the technology.
5	**Prototype/lab validation in relevant environment**	Components are integrated to test the system configuration. Here all system specifications are simulated and validated under relevant conditions, meaning the environment must be very similar to the future work environment.
6	**Pilot system validation in relevant enviroment**	A representative model or complete prototype is demonstrated in a relevant environment to show that the technology is working. The prototype can be demonstrated in a simulated operational lab environment.
7	**Full scale prototype in relevant environment**	Demonstration of a prototype is done in an operative environment and under real conditions. The prototype is fully integrated and very similar or equal to the planned solution.
8	**System complete and qualified**	The technology is working in its final form and under expected conditions. For example, first implementation in at least one project and successful evaluations of the system in an operative environment.
9	**System proven in operation**	The technology in its final form has been in use over a longer period and maintenance is planned and tested.

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway