Norwegian University
of Life Sciences

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

Online Voltage Instability Detection and Prevention Using PMUs – a NEWEPS Perspective

Krishna Solberg
Environmental Physics and Renewable Energy

Engineering is the closest thing to magic that exists in the world.

Elon Musk
CEO of Tesla & SpaceX

Acknowledgements

This thesis was written during the spring of 2021 and constitutes my final submission towards the master's degree in Environmental Physics and Renewable Energy at the Norwegian University of Life Sciences (NMBU). The five years that I have spent working towards this degree have been the most memorable and exciting years of my life. I have made lifelong friends among faculty and peers.

Working on this thesis has been challenging and at times stressful, but also tremendously educational and interesting. Creating such an extensive work has given me a sense of achievement and has inspired me to continue working in the field of power systems.

I would like to thank my thesis supervisor Sonja Berlijn for her guidance, expertise and encouragement during the past months. I also want to thank Kjetil Uhlen and Knut Hornnes for their advice and recommendations regarding the case study. In addition, I would like to thank Andreas Svanes, Ellen Mathiesen and Tobias Korten for their collaboration during these months. Being able to discuss, collaborate and guide each other has made the process far more enjoyable and motivating.

Finally, I would like to extend my sincerest appreciation to my family for their constant support and encouragement. Thanks are also due to my girlfriend Hilde, my lovely housemates and my good friends for always supporting me and keeping me on track with my work.

Ås, May 2021

Krishna
Solberg

Abstract

As a response to climate change, the EU has set a goal of becoming carbon-neutral by 2050. This requires an increased share of renewable energy across the EU's economy, including the energy sector. As a result, power systems will increase in complexity and become more vulnerable to instability. Hence, upgrades and improvements to the power system will be necessary for the years to come. The background for this thesis is the Nordic Early Warning Early Prevention System (NEWEPS) project, a comprehensive project set in motion by the Nordic Transmission System Operators (TSOs). The goal of this project is to create a common information system for stability monitoring and improve the current awareness and control systems. The project focuses on several aspects of the power system, where one aspect is voltage instability detection and prevention. Since voltage instabilities in some cases can lead to voltage collapses, it is desirable to have systems that can continuously monitor the system state and warn system operators of instability. A requirement for this to be implemented is the use of Phasor Measurement Units (PMUs), due to their high sampling rate and time synchronization.

In this thesis, a case study was performed as a way of evaluating how the Norwegian power grid corresponds to contingencies, as well as to confirm general voltage stability theory. Here, Power-Voltage (PV) curves were plotted to find the maximum loadability point of two buses in "Sørnettet", a part of the northern Norwegian power grid. The simulations showed that for the area in focus, the maximum loadability point of the buses was approximately 280 MW when tripping one of three parallel lines. It was also found that a line-tripping closer to the buses resulted in a lower maximum loadability of 205 MW. At the maximum loadability points, the voltages collapsed, which would result in a blackout. Hence, being able to detect when the system is close to these thresholds is critical.

The main goal and research question in this thesis involved risk mitigation of voltage instability and collapse. Consequently, four different types of methods for voltage stability analysis and voltage instability detection and prevention were researched. These were Thévenin Equivalent (TE) models, Machine Learning models (ML), risk matrix assessment and Energy Storage Systems (ESS). Of these four, the TE models were considered

most promising and had the highest Technology Readiness Level (TRL). Two different types of TE models were discussed herein, where the dynamic TE model shows the most potential for implementation in the Nordic power system. A state-of-the-art study with a focus on the Nordic power system will hopefully set a starting point for the NEWEPS project.

For any of these methods to be implemented, further research and testing will have to be done. In addition to verifying the performance of the models on the Nordic power system, economic and practical considerations must be taken into account. The NEWEPS project will include a PhD study, which will further analyze and study methods for voltage instability detection and prevention, and perhaps work on implementation.

Sammendrag

Som en respons på klimaendringene har EU satt et mål om å være karbon-nøytrale innen 2050. Dette krever en økning i andelen fornybar energi på tvers av EUs økonomi, blant annet innenfor energisektoren. Dette vil føre til høyere kompleksitet i kraftsystemet, og risiko for ustabilitet vil øke. Dermed vil oppgraderinger og forbedringer i strømnettet være nødvendig fremover. Bakgrunnen for denne oppgaven er Nordic Early Warning Early Prevention System (NEWEPS)-prosjektet, som er et omfattende prosjekt satt i gang av de nordiske transmisjonssystemoperatorene (TSO). Målet med prosjektet er å lage et felles informasjonssystem for stabilitetsovervåkning og å forbedre de nåværende systemene for oversikt og kontroll. Prosjektet fokuserer på flere aspekter ved kraftsystemet, der ett av dem er oppdaging og forhindring av spenningsustabilitet. Fordi spenningsustabilitet i noen tilfeller kan føre til spenningskollaps, er det ønskelig å ha systemer som kontinuerlig kan overvåke systemtilstanden og advare operatører hvis ustabilitet oppstår. Et krav for at et slikt system skal implementeres er bruken av PMU-er, på grunn av høyere tidsoppløsning og tidssynkronisering.

I oppgaven ble det utført en case-studie for å se hvordan systemet reagerer på en systemfeil. I tillegg blir case-studien sammenlignet med teori om spenningsstabilitet for å undersøke likhetene og eventuelt ulikhetene. I case-studien ble Effekt-Spenning (PV)-kurver plottet for å finne det maksimale lastpunktet til to noder i “Sørnettet”, en del av det nordnorske strømnettet. Simuleringene viste at det maksimale lastpunktet var omtrent 280 MW når én av de tre parallelle linjene ble koblet ut. Det ble også funnet at da en linje nærmere en av nodene ble koblet ut, resulterte det i et lavere maksimalt lastpunkt på 205 MW. Ved de maksimale lastpunktene i alle tilfellene kollapset spenningen, som ville ført til strømbrudd. Å være i stand til å oppdage når systemet er nær disse punktene er derfor meget viktig.

Problemstillingen i oppgaven omhandlet å minske risikoen for spenningsustabilitet og -kollaps. Derfor ble fire ulike typer metoder for spenningsstabilitetsanalyse og oppdaging og forhindring av spenningsustabilitet undersøkt. Dette var Théveninekvivalent (TE)-modeller, maskinlæringsmetoder (ML), risikomatrise og energilagringsløsninger (ESS). Av disse ble TE-modellene ansett som mest lovende og hadde det høyeste TRL-nivået. To

typer TE-modeller ble gjennomgått, der den dynamiske TE-modellen viste mest potensial for implementering i det nordiske kraftsystemet.

For å implementere disse metodene krever det mer forskning og testing. I tillegg til å bekrefte ytelsen til modellene på det nordiske kraftsystemet må økonomiske og praktiske hensyn tas. Som en del av NEWEPS-prosjektet skal det bli utført en doktorgradsoppgave. Denne oppgaven skal videre analysere og studere metoder for oppdaging og forhindring av spenningsustabilitet, samt muligens jobbe med implementering i det nordiske kraftsystemet.

Table of Contents

List of Figures

List of Abbreviations

AC	Alternating Current
AVR	Automatic Voltage Regulator
DTU	The Technical University of Denmark
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage System
EU	European Union
FFNN	Feed Forward Neural Network
GPS	Global Positioning System
HVDC	High-Voltage Direct Current
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
ISI	Voltage Instability Index
ML	Machine Learning
NEWEPS	Nordic Early Warning Early Prevention System
NTNU	The Norwegian University of Science and Technology
OXL	Overexitation Limiter
PMU	Phasor Measurement Unit
PV	Power-Voltage
QV	Reactive Power-Voltage
R&D	Research & Development
RES	Renewable Energy Sources
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SOSPO	Secure Operation of Sustainable Power Systems

ST-VS	Short-Term Voltage Stability
STRONgrid	Smart Transmission Grid Operation and Control
SVC	Static Var Compensator
TE	Thévenin Equivalent
TRL	Technology Readiness Level
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VSM	Voltage Stability Margin
WAM	Wide Area Monitoring
WP	Work Package
ZIP	Impedance-Current-Power

1. Introduction

1.1 Background and Motivation

The changes in global climate due to global warming have led to a plethora of challenges. The Intergovernmental Panel on Climate Change (IPCC) emphasizes in their special report on global warming the importance of limiting the global temperature increase to 1.5 °C compared to pre-industrial levels [1]. To comply with these recommendations, the European Union (EU) has set a goal of carbon neutrality by 2050 [2]. Electrification will be at the forefront of this goal.

The European Green Deal, set in motion by the European Commission, specifically deals with strategies to make Europe sustainable. These strategies are composed of areas across the EU's economy, including industry, transport and the energy sector [3]. The latter will mainly be accomplished through decarbonization and the implementation of Renewable Energy Sources (RES). Hence, the power grid, responsible for providing electricity to the population and industry, should also increasingly be powered by RES. This trend is already quite present in today's power grid and is expected to increase further [4].

Traditionally, the electric power system has been powered by highly controllable energy sources such as fossil, nuclear and hydropower. These sources can to a large extent follow demand, and production can be increased or decreased when necessary. However, in recent years the share of wind and solar power in the power grid has increased [4]. These sources are more difficult to regulate, which can create challenges for the grid. Changes in power consumption patterns will bring forth further challenges. For instance, the ongoing increase of data centers and electric vehicles can affect the overall load of the grid and perhaps create higher power peaks than earlier [5]. This will also result in more variation in the intra-hour electricity demand. To maintain overview and control of the power system, Phasor Measurement Units (PMUs) have been introduced. These units are able to provide measurements of voltage, current and phase angle at a much higher resolution, allowing operators to detect and prevent instabilities faster than previously. However, control systems using PMUs are not yet fully developed, and there are still challenges linked to the integration of the devices. These challenges require innovative and forwardthinking solutions to secure the supply of electricity in the future, where human operation will be the bottleneck.

In an attempt to address the challenges facing the future of electricity supply and distribution, as well as system protection and control, the Transmission System Operators (TSOs) in Norway, Sweden, Finland and Denmark have initiated the Nordic Early Warning Early Prevention System (NEWEPS) project. In collaboration with Nordic universities and research institutions, the goal is to develop a common information system in the Nordic region where stability monitoring and control applications in the power grid are emphasized [6].

1.2 Scope and Limitations

One of the focus areas of the NEWEPS-project deals with voltage instability detection and prevention. Voltage stability is considered an essential part of power system operation. Furthermore, voltage instability may potentially lead to voltage collapse which can have massive economic consequences and affect the security of supply. Having reliable and accurate methods to mitigate the risk of voltage instability is therefore paramount. This thesis will attempt to throw light on and discuss some of the available methods in literature to detect and prevent these instabilities and recommend methods suitable for use in the Nordic power system. Moreover, a case study will be performed to gain a deeper understanding of how the system responds to different scenarios.

As the NEWEPS project specifically deals with the Nordic Synchronous region, the thesis is limited to this region. Access to data was provided by Statnett SF, which further narrows the scope of this thesis since only the Norwegian power system is used for the case study. Nevertheless, it is important to note that the Nordic countries face many of the same challenges. The suggested solutions in this thesis will, therefore, be quite generalized to the entire Nordic synchronous area.

It is also important to mention that this thesis was conducted and written in a period of four months. Hence, priorities had to be made. These include limiting the number of methods to research, as well as the number of simulations performed in the case study. A priority was also made to focus on providing an overview of the challenges and methods available in the literature. As part of the NEWEPS project, a PhD education will be completed. This thesis will likely focus on the implementation and testing of various methods. Hence, it was deemed inexpedient to test any of the methods researched for this master's thesis.

1.3 Research Questions

Based on the scope and limitations mentioned above, this thesis is subject to the following research question:

“How can the risk of voltage instability be mitigated in the Nordic synchronous area using PMUs?”

This question has been analyzed by studying the following:

- “What are today’s challenges regarding voltage stability?”
- “Which methods are available, and can any of them be implemented in the Nordic power system?”

2. The European and Nordic Power Systems

2.1 Electric Power Systems

A conventional electric power system consists of three main components: production, transmission and consumption. Here, large power plants produce electricity by creating rotation in turbines or through other methods that generate a flow of electrons. The power is distributed to consumers through a power grid, which consists of power lines, transformers, as well as the control system that allows the infrastructure to function. The power grid connects the consumers to the power plants, and consumers can thereby use the available power. An important characteristic of the power system is that power must be consumed simultaneously as it is produced. Excluding storage options, this means that the production must always follow the electricity demand. Taking into consideration the losses in the power system, this can be expressed as such:

$$Production = Consumption + Losses, \tag{2.1}$$

where $Production$ is the amount of power produced in the entire power system, $Consumption$ is the amount of power consumed, and $Losses$ is all power lost from the producer to the consumer.

Another trait of most power systems is that they are connected to other power systems. In this way, power systems can cooperate to provide power to each other when one system is unable to produce sufficient power. Exporting or importing power can be considered consumption or production, respectively. Therefore, this introduces two new variables to the equation above:

$$Production + Imports = Consumption + Losses + Exports, \tag{2.2}$$

where $Imports$ is the total power imported into the reference power system, and $Exports$ is the total power exported out of the reference power system.

A method of monitoring the balance in the power grid is to monitor the system frequency. In any alternating current (AC) power system, a standard frequency is determined where the system is in balance. In Europe, 50 Hz was determined to be the standard by 1900 and is still the current standard [7]. If the frequency increases above 50 Hz, more power is produced than what is being consumed. Similarly, if consumption is higher than production, the system frequency will decrease. The TSOs of each country have the responsibility of maintaining the balance, and therefore the system frequency at all times.

2.2 Grid Structure in the Nordic Power System

Although the countries in Europe all operate on the standard 50 Hz frequency, the power systems are divided into several regions. The regional groups shown in Figure 2.1 are known as synchronous areas. Each synchronous area operates under the exact same frequency, meaning that an increase or decrease in production or consumption in one country directly influences the other countries in the same synchronous area [8]. Another consequence is that the TSOs of the countries in the same synchronous area must cooperate very closely to ensure balance in the entire area.

The Nordic synchronous area consists of the power systems of Norway, Sweden, Finland and eastern Denmark [10]. The TSOs of these countries must therefore monitor the entire power system of the synchronous area and change production based on the overall consumption in the area. For example, on days with high wind production in some countries, the other countries can reduce their production from hydro or nuclear power to avoid producing an excessive amount of power.

2.3 Network Planning

An important task of the TSOs is also to plan and develop the power systems for the years to come. The ability to predict trends and future demand will ensure a higher degree of reliability and secure supply. Therefore, several projects and road maps have been set in motion by the European and Nordic TSOs in the last years. A description of three large and important projects will be presented below.

2.4 Ten-Year Network Development Plan

The European power systems will experience many changes in the years to come. It is therefore paramount that these changes are taken into account and handled accordingly.

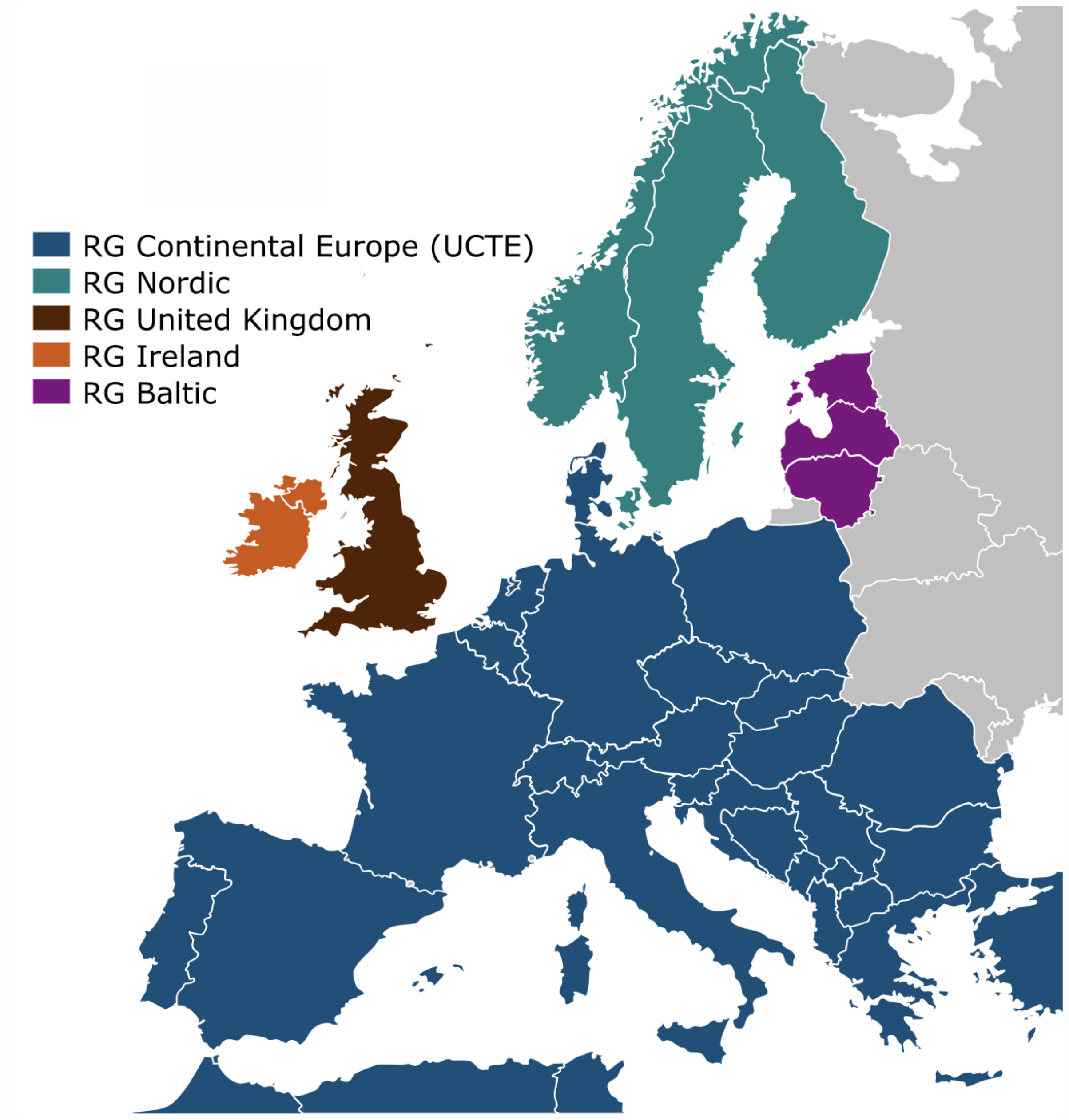


Figure 2.1: The European synchronous areas, which each operate on the exact same frequency [9]. Reused with permission from Sonja Berlijn.

The European Network of Transmission System Operators for Electricity (ENTSO-E) is a collaborative network of the TSOs in Europe. Their goal is to ensure the supply of electricity in the European countries. The organization has published a report named "Ten-Year Network Development Plan" (TYNDP) [11]. This report discusses the expected changes in the electricity sector in the next ten years, from 2020 to 2030, and consequently what needs to be done to secure the supply of electricity.

An important reason for the expected changes in the next ten years is the European Green Deal. As mentioned in the introduction, the European Green Deal is a strategy to attempt to make Europe carbon-neutral by 2050 [3]. Figure 2.2 illustrates the different components of the strategy, which include the focus on circular economy, ecosystems and biodiversity, the mobility sector as well as food and agriculture. Overall, the objective is to decarbonize as many sectors as possible, largely by electrification. This will create an increased demand for electricity, and the Energy Transitions Commission expects that the global electricity demand will increase from 20,000 TWh today to 115,000 TWh in 2050 [12].

Figure 2.2: Summary of the most important measures set forward by the European Green Deal. They feature goals and requirements of the European countries that will assist in accomplishing carbon neutrality by 2050 [9]. Reused with permission from Sonja Berlijn.

This massive upheaval requires a transition in the energy sector. The TYNDP discusses this necessary energy transition and how it can be executed in the most cost- and time-effective manner. The report lists two requirements for this transition:

- "the costs of transforming the system are kept as low as possible, by an appropriate set of investments enabling better market integration and leading to competitive power prices"
- "the continuous secure access to electricity is guaranteed to all Europeans"

The TYNDP addresses a wide variety of projects within the electricity sector across Europe, with a total of 154 transmission projects. It is estimated that these projects will create an additional 90 GW of cross-border transmission capacity. The project portfolio also includes 26 energy storage projects, with a total of 485 GWh capacity. The report also estimates that the projects could ensure 1.7 million jobs in Europe. Although some of the projects in the TYNDP project portfolio include the Nordic region, they are not specifically mentioned in the main report. Therefore, the following section discusses more detailed the challenges and possible solutions in the Nordic power system.

2.5 Challenges and Opportunities for the Nordic Power System

As with the rest of the European power systems, the Nordic synchronous area is facing numerous challenges within the next years. To get an overview of the current and future situation, as well as strategies to ensure a robust grid, the Nordic TSOs have written a report underlining these aspects. This report is named "Challenges and Opportunities for the Nordic Power System" [13] and looks at the period 2010-2025. In this section, the most important findings and possible solutions set by the report will be summarized.

The report outlines several ongoing changes in the Nordic power system. Wind power generation is increasing rapidly with new wind turbines being installed across the Nordic region. The installed capacity from 2010 to 2025 is expected to triple. With RES becoming cheaper and the pressure mounting to reduce the carbon footprint, several traditional power plants are also closing down. This includes nuclear power plants in Sweden, which will be decommissioned earlier than planned. However, Finland is currently building nuclear power plants that will compensate for the capacity loss from Sweden. Another change in the Nordic power system is the increased capacity of high-voltage direct current (HVDC) cables. The increase is expected to be over 50% by 2025 compared to 2016 levels. These cables are used to transfer power between different synchronous areas and will be vital to help regions keep a power balance. These changes will result in a set of challenges, which are also mentioned in the report, the most important being:

- System flexibility
- Generation adequacy
- Frequency quality
- Inertia
- Transmission adequacy

Flexibility in the power system can be defined as the ability to vary production or consumption to maintain balance. In other words, if consumed power (including losses) is larger than produced power, the frequency of the grid will decrease. To restore balance, the system must be able to increase production to match consumption. Hence, a highly flexible system can handle larger variations in production or consumption without jeopardizing the system balance. Flexibility, therefore, requires generation or consumption that can easily be changed whenever necessary. Examples of flexible generation are hydropower, thermal power plants and battery technology. These production types can to a large extent be reduced or increased based on electricity demand. Some new renewable energy sources, such as wind and solar power, do not have the same ability. Generation from these energy sources highly depends on weather conditions. An increased share of wind and solar energy in the power system, while simultaneously decommissioning thermal power plants, will result in reduced flexibility.

While the available capacity for flexibility is slowly reducing, the demand is increasing. Large fluctuations in wind and solar production will require the remaining production units to keep the system in balance. The operational costs of balancing will thus increase, which is undesirable. Traditionally, the Nordic area has had enough flexibility to stay balanced without much external help. This has resulted in a low variation of electricity prices. Leading up to 2025, it is unlikely that this will be the case. As shown in Figure 2.3, the demand is expected to surpass the available capacity, resulting in a possible flexibility shortage.

The other mentioned challenges of generation adequacy, frequency quality, inertia and transmission adequacy are expected to show the same trend as flexibility, as shown in Figure 2.3. With the expected increase in electricity demand discussed in the previous section, the amount of time with sufficient power generation will likely decrease. Without ample upgrades in the transmission lines, adequate transmission capacity will also decrease.

The new renewable energy sources such as wind and solar power lack rotational energy that can be extracted if consumption exceeds production. This rotational energy is known as inertia and plays an important role in maintaining a steady frequency in the grid. As the traditional thermal power plants are decommissioned, the overall inertia of the system is expected to decrease in the coming years, thus affecting the frequency quality. The increased intra-hour imbalances in power consumption will further reduce the frequency quality.

2.6 ENTSO-E RDI Road Map 2020-2030

In addition to the TYNDP, ENTSO-E also published the “Research, Development & Innovation Roadmap 2020-2030” in 2020 [14]. This roadmap addresses many of the same challenges as the TYNDP but focuses more on research and innovation. The report highlights three priority areas for future development and innovation. These priority

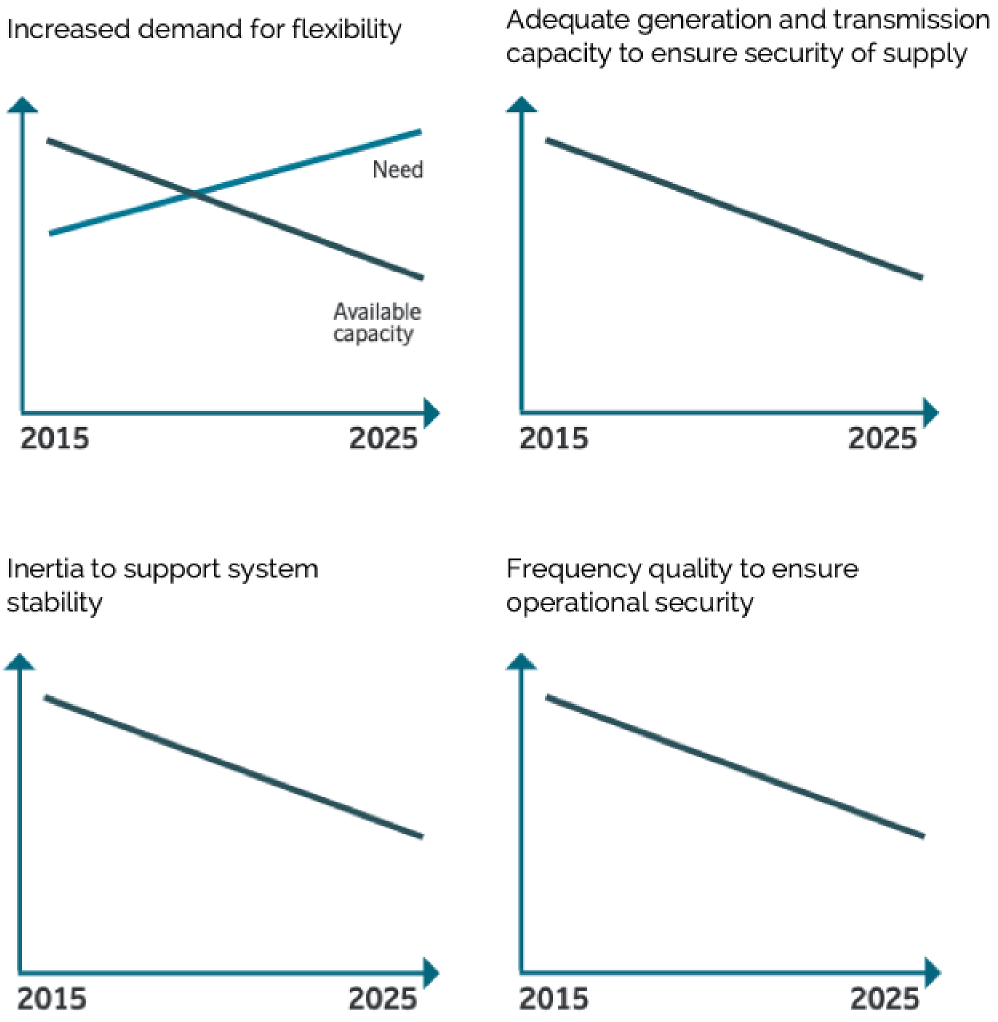


Figure 2.3: Expected trend of flexibility, generation and transmission, inertia and frequency quality from 2015 to 2025. All these categories are expected to decline, and requires upgrading to match the future demand [9]. Reused with permission from Sonja Berlijn.

areas, called clusters, are shown in Figure 2.4. The clusters are further divided into flagship projects, which focus on different strategies and solutions to the challenges in the power system. Cluster 1 mainly focuses on market expansion and integration of the different energy sectors. Cluster 2 deals with upgrading and improving the power grid. Finally, Cluster 3 focuses on the digital infrastructure of the power system and offshore developments. The Nordic power system is closely connected to the European mainland power systems, so these strategies are highly relevant for the Nordic system as well.

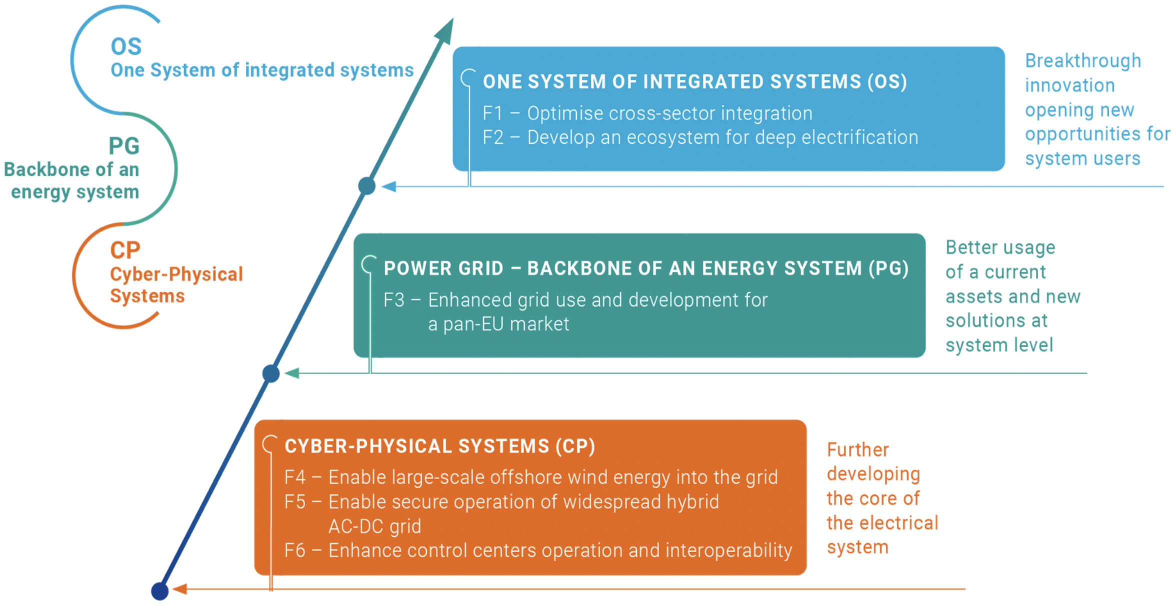


Figure 2.4: Research, development and innovation priority areas, with accompanying flagships [14]. Reused with permission from Sonja Berlijn.

For this thesis, Flagship 6 is most pertinent. This flagship covers the area of control center monitoring and control, with the focus on enhanced information and communication technology (ICT). As the complexity of the power system is increasing, a proper real-time overview will be necessary to keep the system failures to a minimum. An essential requirement for the future monitoring and control system is vendor-independent solutions. Setting a standard for data protocols will prevent a monopoly, and at the same time improve the access to different services. Digitalization and enhanced ICT infrastructure will also increase the risk of cyber-attacks. Therefore, a key part of this flagship is to develop innovative solutions to mitigate the cyber risk. Figure 2.5 illustrates the different milestones of Flagship 6, with the corresponding years the milestones are expected to be reached. For this thesis, “PMU usage for WAM (Wide Area Monitoring)” and “Enhanced methods for more accurate and wider representation of the grid” are the most relevant. Further, the milestone “Pilot for fully automated decision support systems for better supported decisions in the control centres” is closely linked to one of the main goals of the NEWEPS-project mentioned in the introduction.

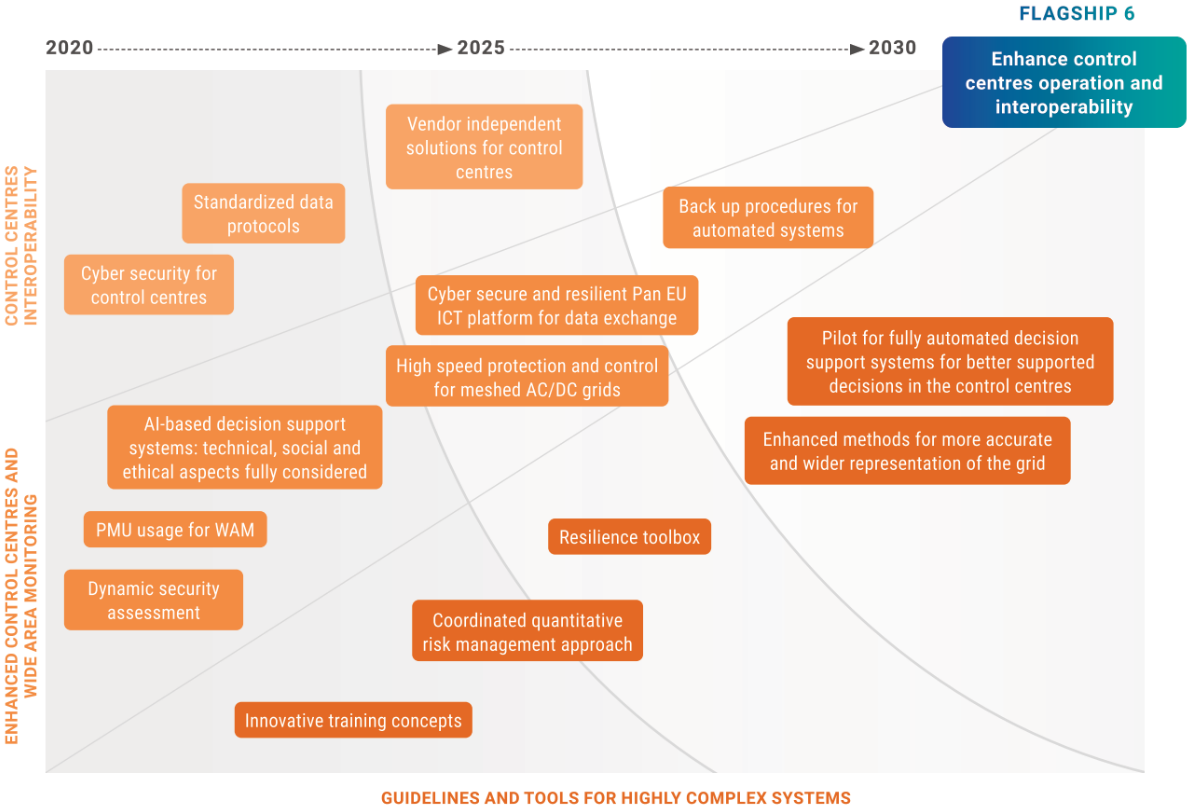


Figure 2.5: The different guidelines and project goals of Flagship 6 leading up to 2030. The overall aim of the flagship is to enhance control center operation and interoperability [14]. Reused with permission from Sonja Berlijn.

3. NEWEPS Project Description, SCADA & PMU

3.1 The NEWEPS Project

The Nordic Early Warning Early Prevention System (NEWEPS) project is a collaboration between the four Nordic TSOs: Statnett (Norway), Svenska Kraftnät (Sweden), Energinet (Denmark) and Fingrid (Finland). Research institutions from these countries are also providing assistance and expertise in research and development. The project was initiated in 2019 and is expected to complete in 2023. Previous projects such as the Smart Transmission Grid Operation and Control (STRONgrid) [15] and the Secure Operation of Sustainable Power Systems (SOSPO) [16] have focused on stability monitoring methods in the Nordic power system. The NEWEPS project aims to develop these methods further and implement a prototype system. This prototype will hopefully allow the methods found in STRONgrid and SOSPO, as well as new methods, to be tested and evaluated [6].

The early warning early prevention system consists of input data from the electric power system, which will be assessed through early warning methods. With assistance from control room personnel, early prevention methods are applied to control the various components of the power system. These methods happen in real-time and will provide further stability. The conceptual overview of the project is illustrated in Figure 3.1.

The project description details certain characteristics of the NEWEPS project. One of the important criteria for the system is its modular structure. As the system will serve many purposes, it is important that various applications and methods can be tested without restructuring the system itself. Standardizing the interfaces between the modules also allows new applications or methods to be implemented into the system easily. Another requirement of the system is that the methods for assessing the input data also will provide the system operators with suggestions on what action needs to be taken. It is also emphasized that if different methods for assessing stability provide different control actions, a coordination module will choose the optimal solution.

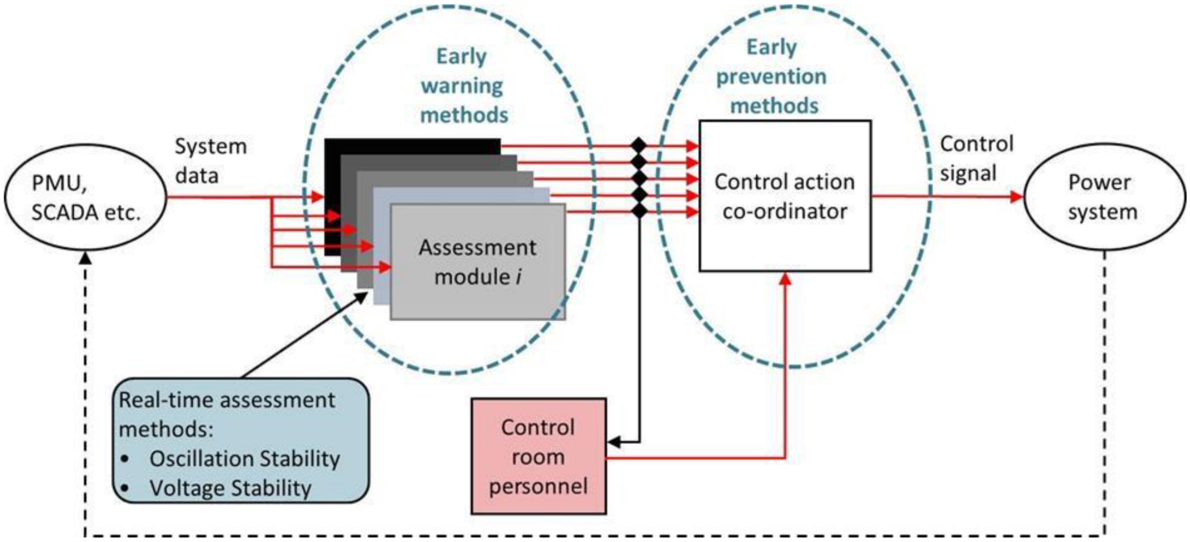


Figure 3.1: Conceptual overview of the early warning early prevention system. Analyzing voltage and oscillation, the aim is to provide system operators with a real-time assessment of the system state. Reused with permission from Sonja Berlijn [6].

The NEWEPS project is divided into "Work Packages" (WP), each focusing on a particular set of challenges in the power grid. These challenges include data platform and interfaces, visualization, power oscillation monitoring, and voltage instability detection and prevention. The WPs are a combination of industrial research and experimental development. Each WP has a specific set of goals, but only the WP that deals with voltage instability will be addressed further.

Work package 4 is titled "Voltage instability detection and prevention" and is regarded as industrial research. The Technical University of Denmark (DTU) is responsible for this WP, but the Norwegian University of Science and Technology (NTNU) as well as Statnett and SINTEF will be contributors. The overall aim of this WP is to develop a prototype of a system that can detect voltage instabilities and calculates the risk of voltage collapse earlier than the current system. The prototype will propose action to mitigate the risk of voltage collapse, which will be implemented into the coordination module mentioned above. The WP will hopefully ensure a higher degree of stability in the grid, which also allows for fewer restrictions in the power flow in the power system. A prerequisite for this WP is the quality of the input data. The sensors measuring the state of the power system must be precise and provide frequent updates to changes in voltage, current and power flow. This will be solved by using PMUs, discussed further below.

3.2 The SCADA System

The next two sections are inspired by the book “Power System SCADA and smart grids” by Thomas and McDonald [17]. This book is recommended for further details regarding these topics.

As mentioned earlier, a power system consists of three parts: generation, consumption and transmission. The latter consists of both the physical as well as the digital infrastructure. For the last decades, power systems have been monitored and controlled using a Supervisory Control And Data Acquisition (SCADA) system. Thomas & McDonald [17, p. 4] define SCADA as:

> “A collection of equipment that will provide an operator at a remote location with sufficient information to determine the status of particular equipment or a process and cause actions to take place regarding that equipment or process without being physically present.”

SCADA has become an integral part of the power system, allowing operators to maintain balance in the increasing complexity. The system consists of two major parts: acquiring data from equipment and supervisory control. Further detailed, the steps involved in the SCADA system is shown in Figure 3.2.

The SCADA system consists of several components which together combine to create an automated system, where information is automatically sent to the system operators, and appropriate action can be made at the operator’s decision. Thomas and McDonald [17] identify four components of the SCADA system:

1. *The remote terminal unit (RTU)* gathers data from sensors in the power grid, transmits the information to the master station, and also acts as a remote controller for the system operators [18].
2. *The master station* is the collection of visual and computational hardware and software that allows the system operators to monitor and control the power system state.
3. *The communication system* is the channels of communication that allows the RTU and the master station to communicate.
4. *The human-machine interface* is responsible for the interface between the operators and the master station, such that decisions that are made can be executed.

Although SCADA is widely used in power grids worldwide, recent changes have created challenges where the conventional SCADA system is insufficient on its own. Because of

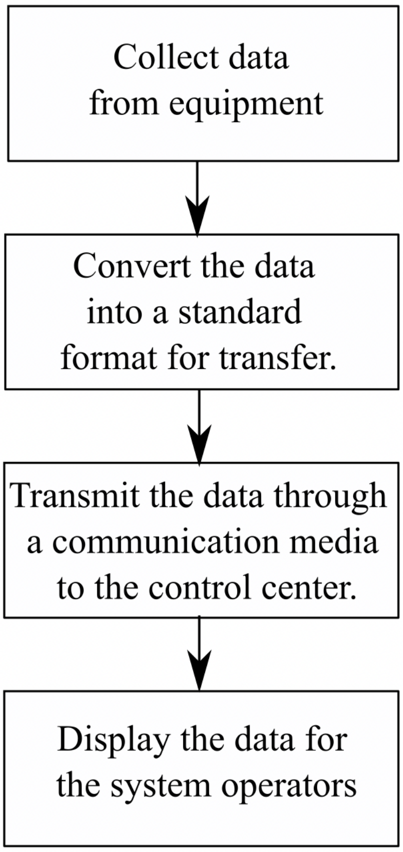


Figure 3.2: The different steps involved in the SCADA system process, from collection of data to an overview for the system operators. Details retrieved from [17].

larger fluctuations of power consumption and production in the intra-hour, as well as more complexity in the grid, the conventional SCADA systems struggle to keep up. Larger and more frequent fluctuations require data sampling at a higher resolution, such that instabilities can be detected more rapidly [17]. The current SCADA systems are unable to report data at rates faster than once every four to six seconds [19]. In addition, the measurements from RTUs are asynchronous, meaning that the angle difference between two buses cannot precisely be assessed [20]. To acquire synchronous measurements and data in a higher time resolution, Phasor Measurement Units (PMUs) have been introduced.

3.3 PMUs

Much like the traditional RTUs, PMUs measure voltage and current at a certain area in the power grid, and the data information is sent to the system operators. PMUs however, are able to measure these quantities at a much higher rate, up to 200 times per second for a 50 Hz system [21]. Figure 3.3 illustrates the difference in what PMUs can measure, compared to the traditional SCADA system.

A measurement of voltage or current and a phase angle is called a phasor. A phasor,

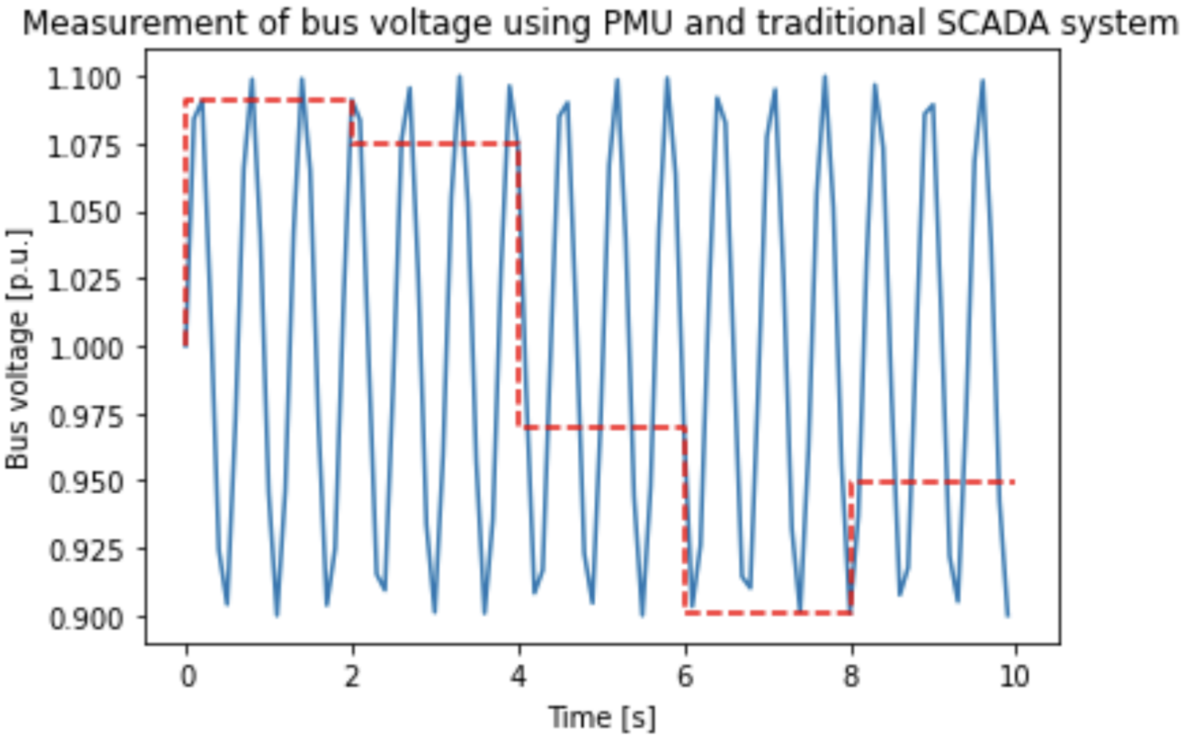


Figure 3.3: Illustration of how PMUs would measure bus voltages compared to the traditional SCADA system. The increased resolution allows for earlier detection of discrepancies.

therefore, describes both a magnitude and the phase angle, and can be represented by a sinusoidal waveform:

$$V(t) = V_m cos(\omega t + \delta_0), \tag{3.1}$$

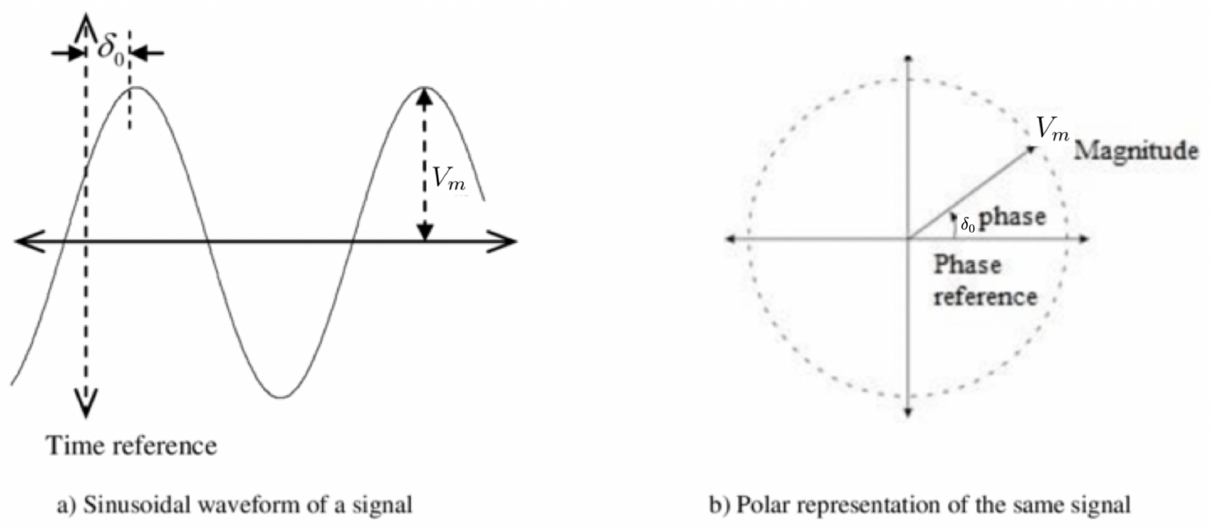
where V_m is the maximum magnitude of the voltage signal, ω is the instantaneous frequency, given as $2\pi f$, and δ_0 is the angular starting point of the waveform. This equation can also be written in the phasor notation:

$$\overline{V} = V_m \angle \delta_0, \tag{3.2}$$

where the overline indicates a phasor. Figure 3.4 shows two ways of representing a phasor: in sinusoidal and polar form. The voltage is usually expressed as a root-mean-squared (rms) value. The corresponding rms value of the voltage is given by:

$$\overline{V}_{rms} = \frac{V_m}{\sqrt{2}} \angle \delta_0. \tag{3.3}$$

One specific feature of PMUs is that the measurements from different locations are syn-



a) Sinusoidal waveform of a signal

b) Polar representation of the same signal

Figure 3.4: Illustration of a phasor with sinusoidal (a) and polar (b) representation. Reused with permission from Bogdan Vicol [22].

chronized using information from the Global Positioning System (GPS). This allows the relative phase angles between these locations to be directly measured. The benefit of this is that the system operators will get a better and more precise overview of the entire system [19]. Also, PMUs can be strategically placed in different areas of the power grid to avoid installing them at all locations without affecting the visibility [23]. Installing a sufficient amount of PMUs in the power grid will allow system operators to detect deviations earlier than before, and the possibility to correct these deviations will also increase.

Figure 3.5 illustrates how a power system with PMUs can operate. PMUs are installed at substations in the power system, and the measured data are sent to a phasor data concentrator. The SCADA system will provide the system operators with relevant information, and corrective measures can be taken if necessary. The data can also be analyzed using an analysis program to gain more insight into the data.

The advantages PMUs give to the system operators have resulted in many PMUs being installed in the Nordic power grid. As an example, Figure 3.6 shows the amount of installed and planned PMUs in the Norwegian power grid, along with the number of measurements these sensors take. The numbers for this figure were made in 2019, and according to an expert on the field at Statnett, there are in the spring of 2021 approximately 120 PMUs in Norway, and 145 PMUs in the rest of the Nordic countries [24]. Many more are expected to be installed in the next few years.

One challenge with the use of PMUs is the concern of cyber security. With an increased level of digitalization in the power system, the risk of cyber attacks also increases. Therefore, this aspect also has to be taken into consideration. Nevertheless, this is beyond the scope of this thesis and will not be discussed further.

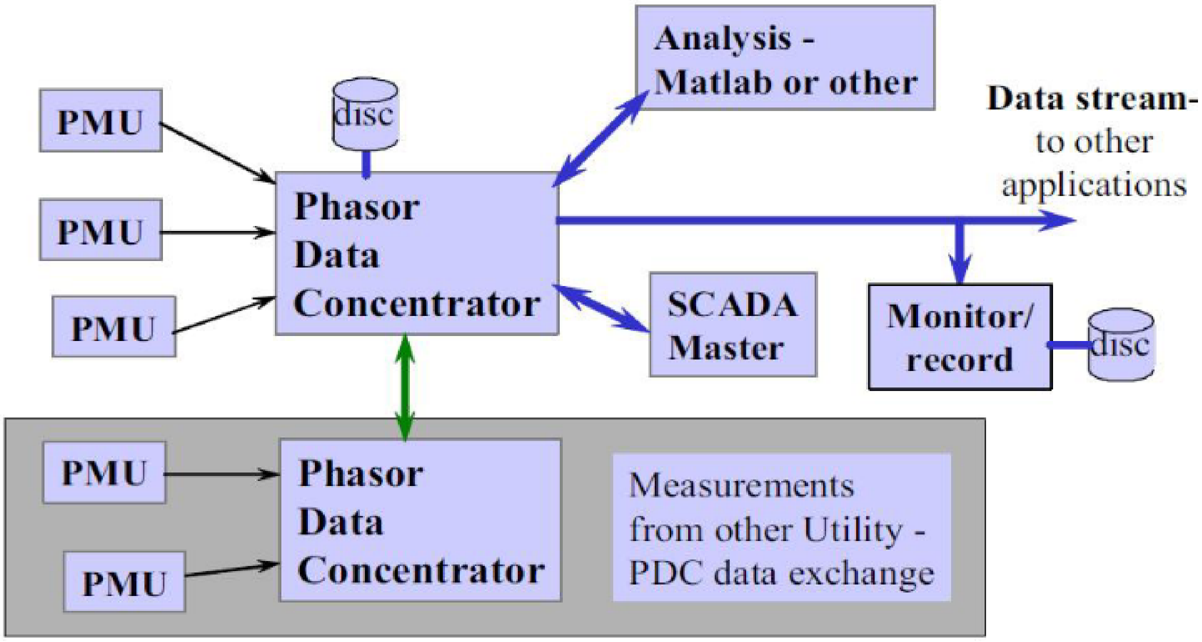


Figure 3.5: An overview of a power system with PMUs installed. The PMUs will take measurements of the system state, and these measurements can be assessed real-time as well as analyzed later. Reused with permission from IEEE [2018].

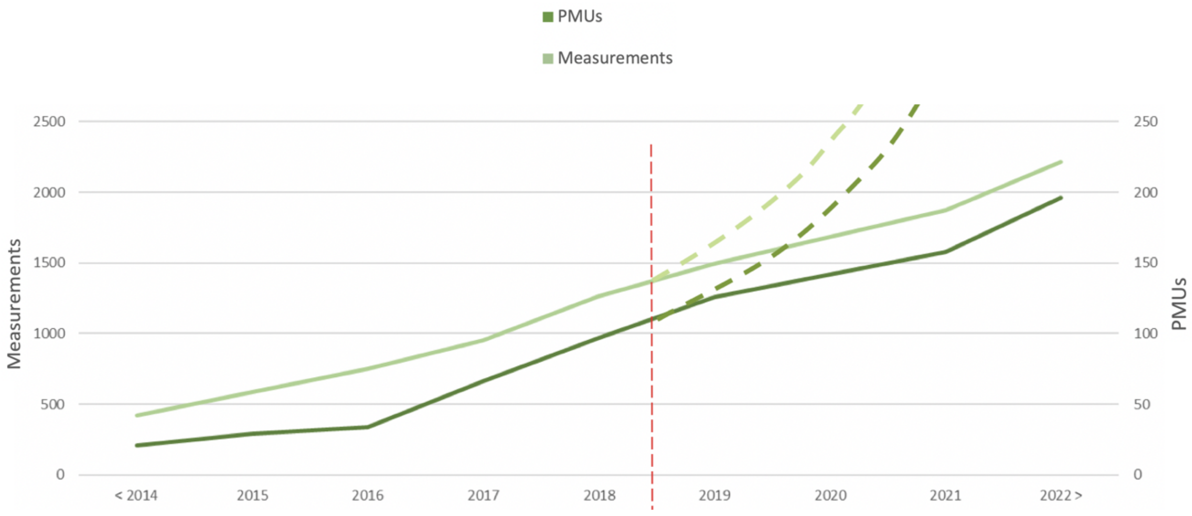


Figure 3.6: An overview of the currently and planned installed PMUs in the Norwegian power grid leading up to 2022. An optimistic scenario is shown with the dashed lines [25]. Reused with permission from Sonja Berlijn.

4. Methods

4.1 Literature Selection

The main goal of this thesis is to research different methods of improving voltage stability and predicting and preventing voltage instability. This literature selection aims to get an overview of the current methods used today, and which ones can be utilized in the Nordic power system.

Using Google Scholar, the Institute of Electrical and Electronics Engineers (IEEE) database, ResearchGate, Scientific American and the Norwegian University of Life Sciences' library, a list of articles were picked out that were deemed relevant. Before discussing the separate methods, some background theory is considered necessary. Therefore, the articles are separated into two categories:

- Voltage stability theory
- Methods for monitoring voltage stability and detection and prevention of voltage instability

For the literature selection in the first category, the aim was to acquire a thorough understanding of the fundamentals of voltage stability and the driving forces of voltage instability. Books and articles were chosen by their ability to expound the phenomenon of voltage stability in an understanding way, as well as how frequently they are cited by others. The publication year of the books and articles was not strongly weighted, as the physics does not change. To find these articles and books, the following search strings were most frequently used:

("Voltage stability" **OR** "VS" **OR** "Voltage instability" **OR** "Voltage collapse")

AND

("Theory" **OR** "Definition" **OR** "Power system")

For the second category, it was desirable to find several different techniques and methods that are used to monitor stability and detect and prevent instability. A prerequisite was that these methods were able to be performed online or were using PMU data. Therefore, the following search strings were used:

(“Voltage stability” **OR** “VS” **OR** “Voltage instability” **OR** “Voltage collapse”)

AND

(“PMU” **OR** “Online” **OR** “Real-time”)

AND

(“Methods” **OR** “Analysis” **OR** “Techniques”)

From this, several relevant methods were found. The following technologies were chosen, and will be discussed in Chapter 7:

- Thévenin equivalent models
- Machine learning models
- Risk matrix
- Energy storage solutions

In the literature selection regarding the different methods, articles published before 2016 were not included, as they were considered somewhat outdated.

4.1.1 Technology Readiness Level

In the Research & Development (R&D) field, there is usually a desire to explain how far a particular technology has come. One way of classifying this is with a Technology Readiness Level (TRL) scale. These scales do not have a universal standard. Thus, there is some variation among different companies and industries. Figure 4.1 shows the scale used by Statnett, ranging from TRL 1 to TRL 9, which will be used in this thesis [26]. In Appendix A, a table with an accompanying detailed description of each TRL is presented. An estimated TRL will be given to the methods introduced in Chapter 7, based on which description most closely resembles the current state of each method. Here, a TRL will be given by how far the technology has come globally and not only in the Nordic power system.

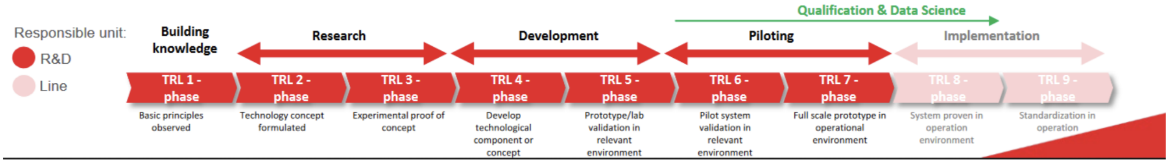


Figure 4.1: Illustration of the different TRL-levels used to classify how developed a technology is. These levels are used by Statnett. Reused with permission from Sonja Berlijn.

4.2 Case Study

In addition to the literature selection, this thesis will examine a simulation of a contingency in the power grid. The goal is to analyze how the system responds to this contingency, and whether the grid responds as expected. The case study will focus on a part of the northern Norwegian power grid which is considered quite weak. More precisely, the focus will be on a part often referred to as “Sørnettet”, located around the Lofoten and southern Troms area. As the detailed structure of the Norwegian power grid is not public domain, it cannot be shown in this thesis. However, Figure 4.2 shows where this part of the power system is located.

The area is dependent on power transmission from the surrounding power grid due to a shortage of power production. Three parallel transmission lines, called “Vestsnittet”, are responsible for providing Sørnettet with a sufficient power supply. According to Statnett, one of the lines is in poor condition. Additionally, two of the lines are located in an area prone to landslides. Should a landslide occur, both lines could be tripped. Recovering these lines could take days and have immense consequences [27].

By performing a line tripping on one of the lines going out in the Lofoten archipelago while simultaneously increasing the load in the area, it will be investigated how the power grid responds. The results will be analyzed and compared to the theory presented in Chapter 5.

Generally, power systems are very complex, and it is usually undesirable to analyze them analytically. Therefore, computer simulations are performed on smaller test systems to study different phenomena. In this thesis, a test network that highly resembles “Sørnettet” will be used. The simulation will be carried out in the power system software tool PSS/E made by Siemens. The program features a myriad of analyzing features, including power flow, contingency analysis, dynamics and voltage stability. As a novice in this program, a significant amount of time was allocated to learning the necessary skills to perform the analysis, found in the PSS/E Program Operation Manual [28].

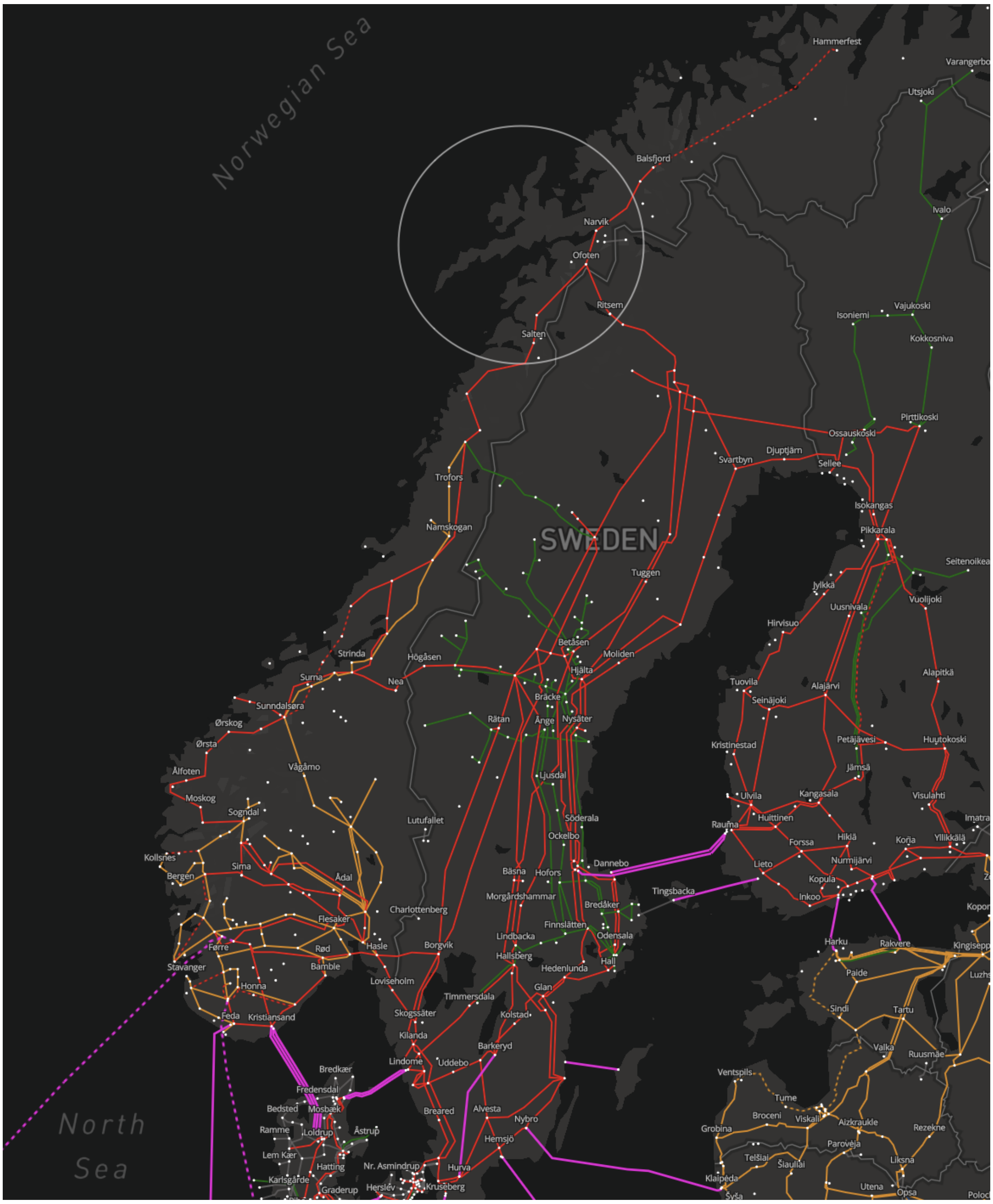


Figure 4.2: A high-voltage grid map of the Norwegian power system. The white circle in the northern part of Norway indicates the area of interest for the case study. Retrieved from [29].

The details regarding the contingencies will be given in Chapter 6, along with the results of the simulations.

5. Stability

5.1 Power System Stability

The IEEE/CIGRÉ Joint Task Force suggests the following definition for power system stability [30, p. 1388]:

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

Thus, stability analysis involves determining the main causes of instability, and the methods to sustain a stable system. According to [31], power system operation relies on three principal quantities:

- nodal voltage angle, δ
- frequency, f
- nodal voltage magnitude, V

These quantities divide power system stability into three categories: rotor angle stability, frequency stability and voltage stability, as shown in Figure 5.1.

Rotor angle stability can be defined as the synchronous machines' ability to maintain synchronism after a disturbance. In other words, the synchronous machines must be able to maintain or restore equilibrium between mechanical and electromagnetic torque [30]. If stability in the system is unable to persist, some generators may lose synchronism with other generators. As presented in Figure 5.1, rotor angle stability is divided into small disturbance angle stability and transient stability.

Similarly, frequency stability can be defined as the power system's ability to maintain a stable frequency both under normal operating conditions and after a severe disturbance [30]. As explained previously, frequency instability is caused by a discrepancy between power production and load. Usually, there are predetermined frequency boundaries that

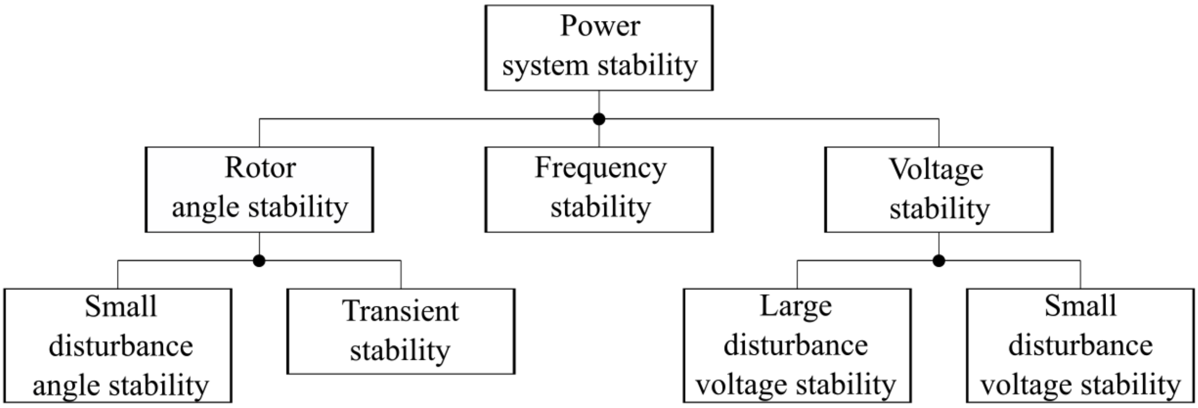


Figure 5.1: Classification of different types of stabilities in a power system. Details of flowchart retrieved from [31].

the system should operate under. Therefore, frequency stability depends on the system's ability to keep the frequency in the determined range. In the Nordic synchronous area, this range is 50 ± 0.1 Hz.

Lastly, voltage stability can be defined as the power system's ability to maintain stable bus voltages both before and after a disturbance [30]. This type of stability will be discussed in more detail in the next section.

5.2 Voltage Stability

As shown in Figure 5.1, voltage stability can be divided into two categories: small disturbance voltage stability and large disturbance voltage stability [30]. Small disturbance voltage stability is the ability of a power system to maintain steady voltages following a small disturbance, such as an incremental increase or decrease in system load. On the other hand, large disturbance voltage stability is the ability of a power system to maintain steady voltages at all buses after a large disturbance. Examples of large disturbances can be loss of generation or system faults. Both types of stabilities are dependent on the system and load characteristics, as well as system controls.

In addition, the IEEE/CIGRÉ Task Force distinguishes between short-term and long-term voltage stability. Short-term voltage stability (ST-VS) is measured in the order of a few seconds and involves components such as electronically controlled loads, induction motors and HVDC converters with fast-acting load dynamics. Long-term voltage stability (LT-VS) involves components such as tap-changing transformers, generator current limiters and thermostatically controlled loads, which are slower acting. The study period of interest could be in the order of many minutes, which requires long-term system simulations for analysis.

A more detailed description of the components and equipment mentioned above can be found in [31]. Before further discussing voltage stability, a background of the physical properties of voltage stability analysis will be presented.

5.2.1 Power Circuit Theory

As a starting point, consider a simple model of a two-bus system, shown in Figure 5.2, known as a Thévenin equivalent network [21]. For simplicity, the transmission line is purely reactive, with impedance jX. Also, the generator will be considered an ideal voltage source with voltage magnitude E. Under balanced three-phase, steady-state conditions, these power flow equations describe the system operation:

$$P = -\frac{EV}{X} sin\delta \tag{5.1}$$

$$Q = -\frac{V^2}{X} + \frac{EV}{X} cos\delta, \tag{5.2}$$

where P is the active power consumed by the load, Q is the reactive power consumed by the load, E is the magnitude of the generator voltage, V is the magnitude of the voltage at the load bus, X is the reactance, which in this case is the aforementioned transmission impedance, and δ is the difference in angle between the generator and the load buses.

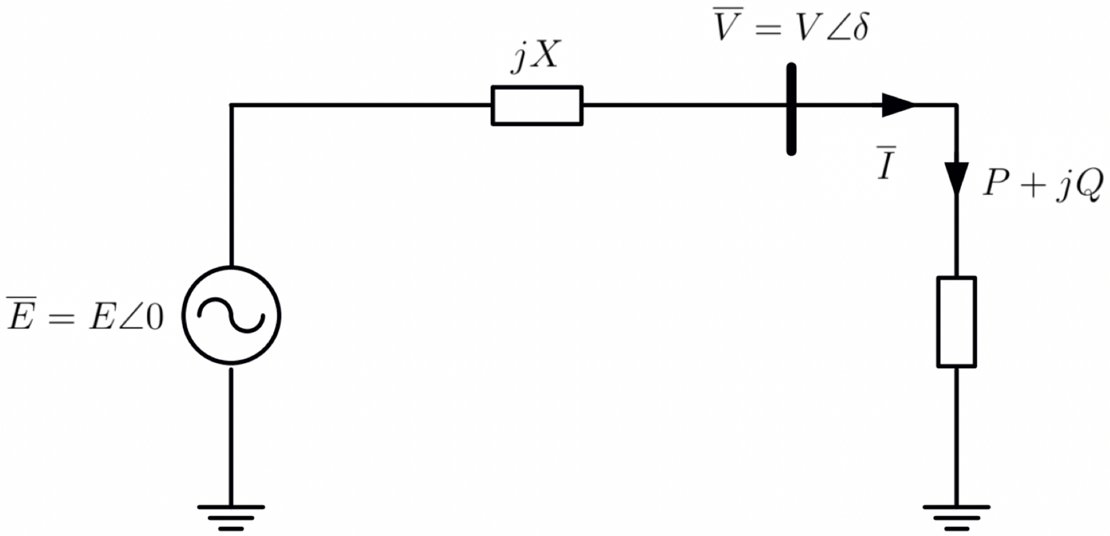


Figure 5.2: A simple two-bus system with a constant voltage source, an impedance and a load.

Solving for V gives:

$$V = \sqrt{\frac{E^2}{2} - QX \pm \sqrt{\frac{E^4}{4} - X^2P^2 - XE^2Q}}. \tag{5.3}$$

In (5.3), the expression under the second root,

$$\frac{E^4}{4} - X^2P^2 - XE^2Q \geq 0, \tag{5.4}$$

has to be fulfilled for the solution of V to be valid. When this condition is fulfilled, V yields two solutions, indicated by the ± sign. Figure 5.3 shows the plot of equation (5.3), where V varies as a function of P and Q. The part of the solution with a plus sign corresponds to the upper part of the surface on the figure. Similarly, the part of the solution with a minus sign corresponds to the lower part of the surface. When (5.3) is equal to zero, the values of V lie on the "equator", or between the upper and lower part of the surface. On the equator and the surface of Figure 5.3, the solutions correspond to the maximum power points, i.e. where P and Q have their maximum values for different V [32].

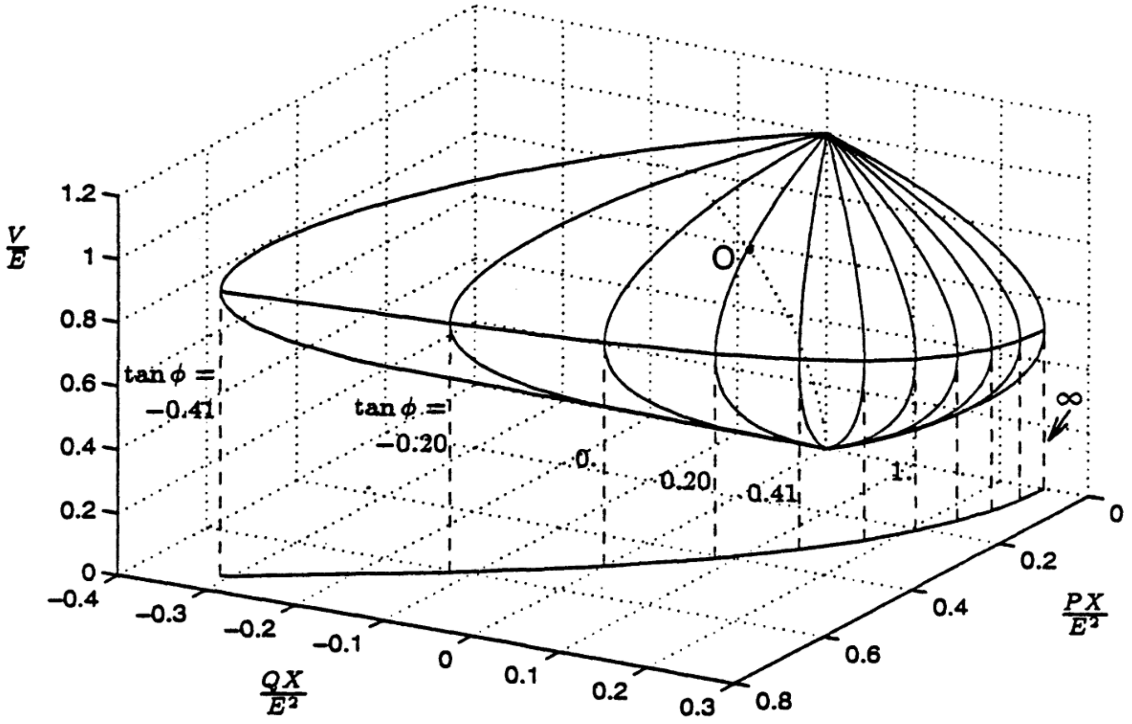


Figure 5.3: Voltage, $\frac{V}{E}$, as a function of active and reactive power. Reused with permission from [32].

5.2.2 PV and QV Curves

Figure 5.3 also shows "meridians", solid lines following the surface of the "sphere". These meridians are intersections with vertical planes $Q = Ptan\phi$ (assumed constant power factor), where ϕ is the power factor angle. The dotted lines are values of $tan\phi$ when ϕ varies from $-\frac{\pi}{8}$ to $\frac{\pi}{2}$ with increments of $\frac{\pi}{16}$. The meridians can be projected onto the Power-Voltage (PV) plane, and give the curves of voltage for different values of active power, for different values of tan ϕ. This plot is known as a PV curve and is shown in Figure 5.4. Similarly, the meridians can be projected onto the Reactive power-Voltage (QV) plane and this plot is known as a QV curve. These curves are also called "nose curves", due to their pointy shape. At the maximum level of active power, there is only one solution. Here, the voltage, and therefore the current has only one value. For all other lower values of the active power, there are two solutions, one where the voltage is higher and the current is lower, and vice versa. The same concept applies to the QV curve. These curves are very important in the analysis of voltage stability [32].

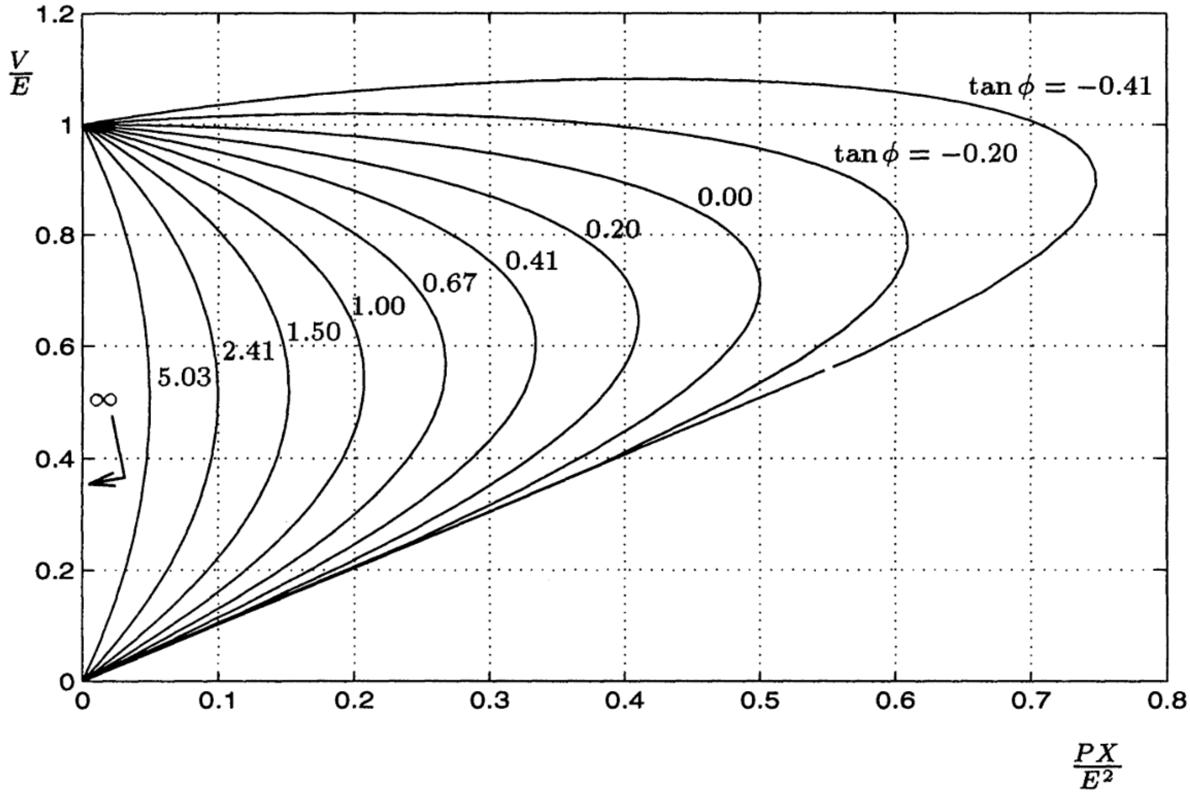


Figure 5.4: A PV curve, where voltage, $\frac{V}{E}$, is shown as a function of active power [32]. Reused with permission from Thierry van Cutsem.

5.2.3 Main Causes of Voltage Instability

Loads are an important driving force of voltage instability. During and after a disturbance, loads affect the system stability in different ways. Consider the widely used exponential load model:

$$P = zP_0 \left(\frac{V}{V_0}\right)^{\alpha} \tag{5.5a}$$

$$Q = zQ_0 \left(\frac{V}{V_0}\right)^{\beta}, \tag{5.5b}$$

where z is a specified demand, P_0 and Q_0 are the active and reactive power respectively for $z = 1$, V_0 is the reference voltage and α and β are voltage impacts on real and reactive power respectively [21]. By choosing arbitrary values for α, β, P_0 and Q_0, Figure 5.5 can be drawn. The solid line represents all possible demands and is known as the network characteristic [32]. Points A and B correspond to different operating points with different demands z but with the same power P. By increasing the demand z slightly, which is indicated by the dotted lines, point A moves down right on the solid line, resulting in a higher power but slightly lower voltage. This is how a power system should operate. However, when slightly increasing the demand z, point B moves down left, resulting in both lower power and lower voltage. Here, the operating point is unstable, as the power system is unable to deliver the required power.

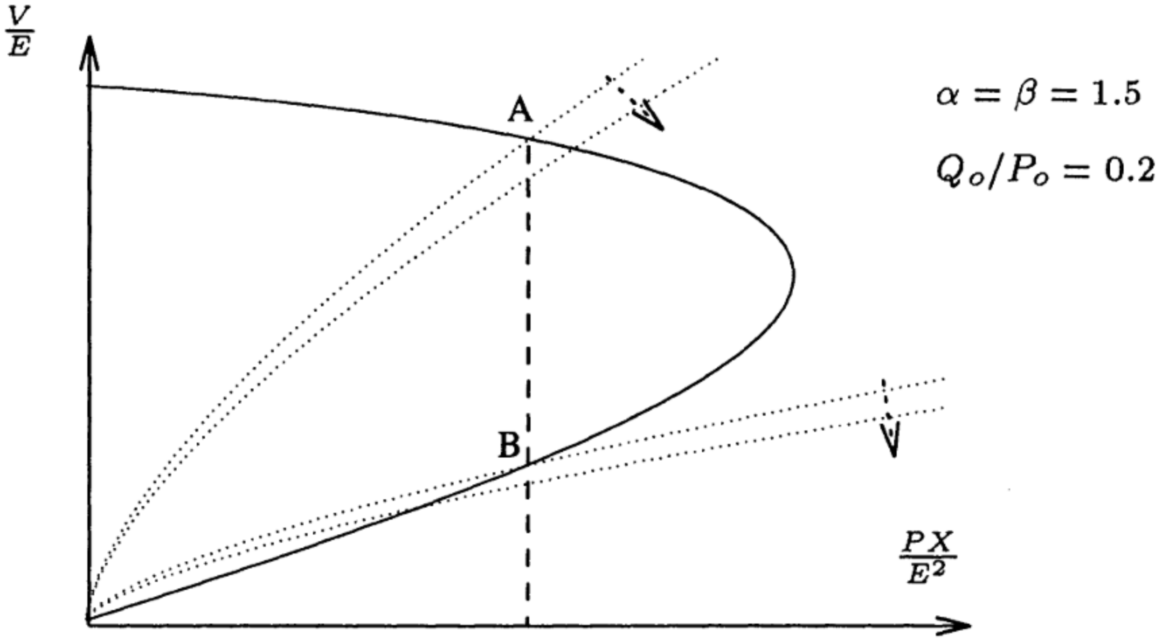


Figure 5.5: Example of two possible operating points on the PV curve. Point A is a stable operating point, while point B is an unstable point [32]. Reused with permission from Thierry van Cutsem.

Another important reason for voltage instability is a disturbance. The vertical dashed line in Figure 5.5 is known as the load equilibrium characteristic [32]. A large disturbance can occur with the tripping of a transmission line, a power plant error, or other reasons that decrease the generated power supply. The main causes of disturbances in the Norwegian high-voltage power grid are shown in Figure 5.6. In the two-bus example previously mentioned, the X will increase and/or E will decrease. If the disturbance is large enough, the network characteristic will shrink until the solid line in Figure 5.5 no longer intersects with the load equilibrium characteristic. Therefore, the system is unable to recover, and a voltage collapse may occur.

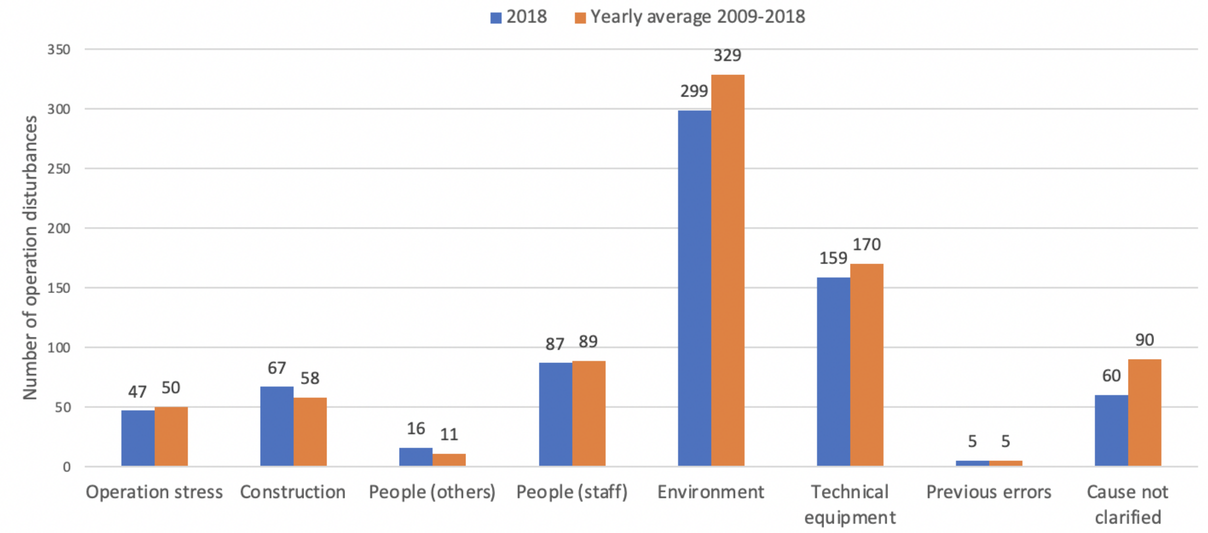


Figure 5.6: Number of disturbances in the Norwegian high-voltage power grid based on triggering cause. Data from [33].

Finally, insufficient reactive power delivered from the generators can also cause voltage instability. As illustrated in the QV curves in Figure 5.7, the voltage can be controlled by injecting or absorbing reactive power into or from the system, for a given per unit active power p. The QV curve, therefore, describes the required reactive power to keep the voltage at the desired level. If a disturbance or an increase in load results in a decrease in voltage, the generators will have to provide more reactive support to the system to increase the voltage back to nominal levels. The reactive power margin describes the distance between the present reactive power and the reactive power at the critical point. The critical point is analogous with the tip of the nose curve in Figure 5.4. If the system cannot deliver the required reactive power, the system is prone to voltage instability. The reactive power that the generators can provide is limited by the field current rating, the armature current rating and the maximum turbine power rating [34].

The field winding and armature winding are both subject to overheating. Therefore, there are protective measures to ensure that the components are unharmed. The overexcitation limiter (OXL) measures the field current of the generator and determines if it is above a certain threshold [34]. If so, the field current is brought back below the threshold by the automatic voltage regulator (AVR) to avoid overheating. An armature current limiter

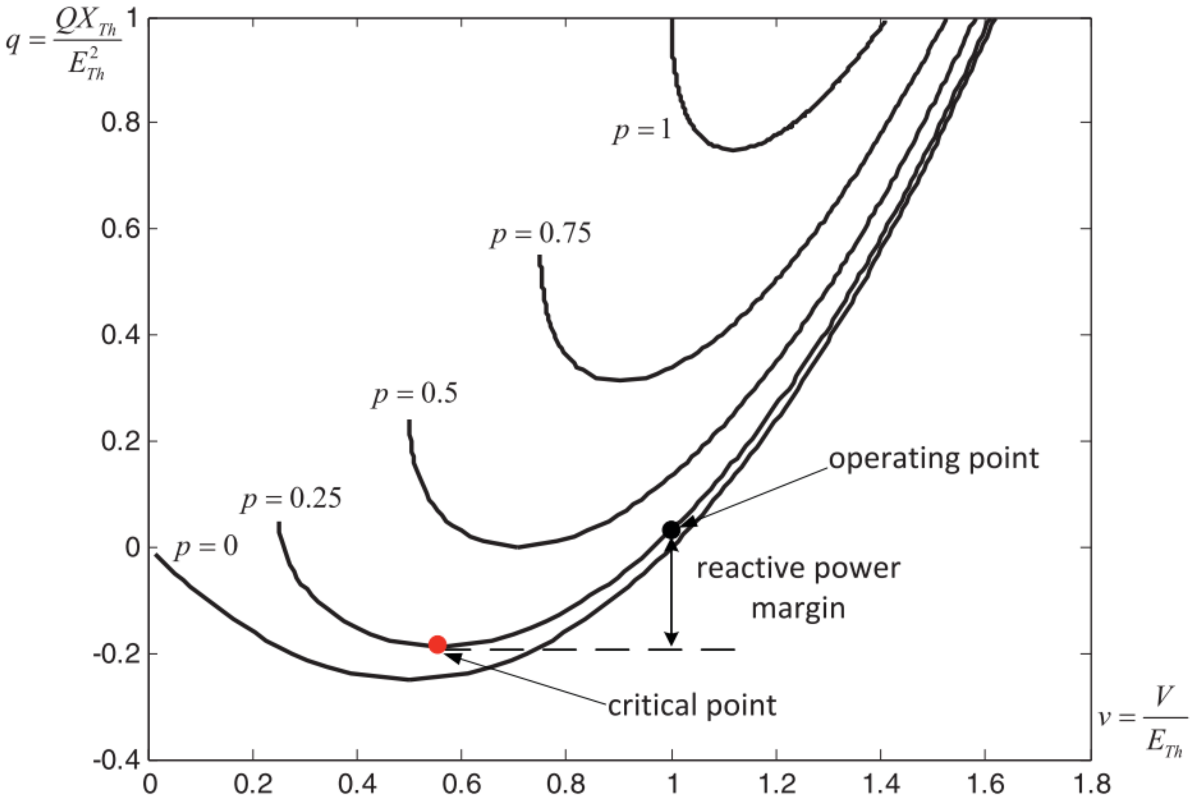


Figure 5.7: A typical QV curve for different load powers, p. The critical point is the point at which voltage instability occurs. Reused with permission from [34].

performs the same task for the armature current. If the system is unable to deliver the required reactive power support, there is a risk of voltage instability. Therefore, it is important to monitor the reactive power reserves.

5.2.4 Importance of Voltage Stability

Voltage stability is a primary concern in the power system. Equipment in industry and households require a certain voltage. If a severe disturbance occurs, the voltage might fall outside the set voltage range. This can cause flickering in lights, and in a worst-case scenario destroy electronic equipment [35]. Voltage collapse, which is a result of voltage instability that is unable to stabilize itself, will also leave households and industries without power altogether. In addition to the lost income of the TSO, loss of power usually has many negative consequences in society. Having a power system with a high degree of voltage stability is therefore very desirable.

5.3 Countermeasures Against Voltage Instability

Some of the newer and more complex methods for analyzing voltage stability and preventing instability are discussed in Chapter 7. However, some important countermeasures already exist in today's power system.

First of all, power systems are usually built around the principle of the (N-1) contingency criterion. This criterion requires the system to continue to operate even if one generation or transmission component fails [36]. This has been an important part of the power system operation and is implemented in the planning and building stage. Although the (N-1) contingency criterion is very important, the increased stress on today's power system requires other solutions as well.

As discussed in the previous section, insufficient reactive power is a major cause of voltage instability. Therefore, having adequate reactive power in the system should be of utmost importance. Shunt capacitors are used as a power factor correction, which increases power transfer capacity. In this way, the shunt capacitors improve the voltage profile in the system. By allowing some shunt capacitors to be disconnected, they can be switched in when necessary to aid in voltage control. Similar to shunt capacitors, static VAR compensators (SVCs) are also components used to adjust the power factor as well as provide voltage stability. The SVC can both generate and consume reactive power. Unlike the static shunt capacitors, SVC systems are active and can continuously be adjusted to deliver according to system needs [37]. They are more fast-acting than shunt capacitors and are for this reason widely used in electric power systems to aid in keeping the system stable. Finally, shunt reactors are used to absorb reactive power in the transmission system. Disconnecting these can be a solution if the system is approaching voltage instability.

Another countermeasure against voltage instability is the increase in generation. Generators that are already running and close to the instability area can if possible adjust both active and reactive output power [38]. However, increasing active power decreases reactive power and vice versa, meaning that an optimization method might be necessary, which does not always performs perfectly. If available, reserve power plants can be started up to assist in mitigating long-term voltage instability by delivering excess reactive power to the system.

A third method involves shedding loads from the system if the voltage decreases below a certain threshold. Disconnecting loads reduces system stress, and the voltage will increase back to normal operating levels [34]. Here, the challenge lies in determining the right threshold, as well as which and how much load should be shed. Also, there are cases where high voltages indicate signs of instability. This will not be picked up using this method.

6. Case Study Details and Results

6.1 Contingency Description

As mentioned in Chapter 4, the area of focus is the Lofoten archipelago. Three parallel lines deliver power to this area. In this thesis, four contingencies will be simulated. The first two contingencies involve tripping one of the lines, and thereafter increasing the load power demand to the area. The voltage of certain buses in the grid can be monitored while gradually increasing the load of the area. As discussed in Chapter 5, a PV curve can thereby be plotted. These curves can indicate how the power system responds to this type of change. The two first cases will monitor two different buses after tripping the same line, hereby called Bus 1 and Bus 2. The contingencies will be referred to as Contingency 1 and Contingency 2 respectively.

By tripping a line further out in the Lofoten archipelago, it will most likely be more challenging for the power system to divert the necessary power through other lines with less capacity. Therefore, a third contingency of this kind will also be performed. Bus 2 from Contingency 2 will be monitored, to see if some line trippings are more problematic than others. This contingency will be referred to as Contingency 3.

In summary, the first three contingencies were performed as such:

1. PSS/E:
    - Open the "Sørnettet" test system
    - Disconnect the desired transmission line
    - Gradually increase the load in the area of the desired bus
    - Solve the system for each load increase and note the voltage at the bus
2. Excel:
    - Insert power flow and voltage values
    - Plot the PV curves

As discussed in Chapter 5, the rate of change of voltage increases when the system is closer to maximum loadability. Therefore, in all three contingencies, the load will increase less as the voltage drops further, to ensure sufficient data points where the voltage begins to collapse.

Finally, Contingency 4 will be a dynamic simulation. Unlike the three previous contingencies, this simulation will plot the voltage as a function of time. This will provide a more thorough understanding of how the system responds and the time frame of a voltage collapse. Here, a line similar to the one in Contingency 1 will be tripped. Subsequently, the load in the area will be increased until the voltage collapses. The two buses from the previous contingencies will both be monitored. In PSS/E, a dynamic simulation continuously monitors the voltage, and the output is similar to what a PMU could measure. Hence, step-wise noting the voltage throughout the simulation is unnecessary.

In summary:

1. PSS/E:
    - Open the “Sørnettet” test system
    - Disconnect transmission line and run dynamic simulation
    - Gradually increase the load in the area and update the simulation
    - Save the dynamic simulation output file
2. PSSPLT:
    - Load the output file
    - Add axis ranges and plot titles
    - Plot the voltages at the two buses

6.2 Results of Case Study

Figure 6.1 shows the PV curve of the first simulated contingency, where one of the main 130 kV lines was tripped. The load in the area was initially 147 MW and as the load is increased incrementally, the voltage at the monitored bus also changed. The maximum loadability in this contingency was 282 MW and increasing the load further resulted in a decline in the power delivered to the area. Before the voltage collapse occurred at the node, several other lines reached full capacity.

Similarly, Figure 6.2 shows the PV curve of another bus after the same line tripping. Here, the maximum loadability was 283 MW, and the voltage quickly collapsed after this

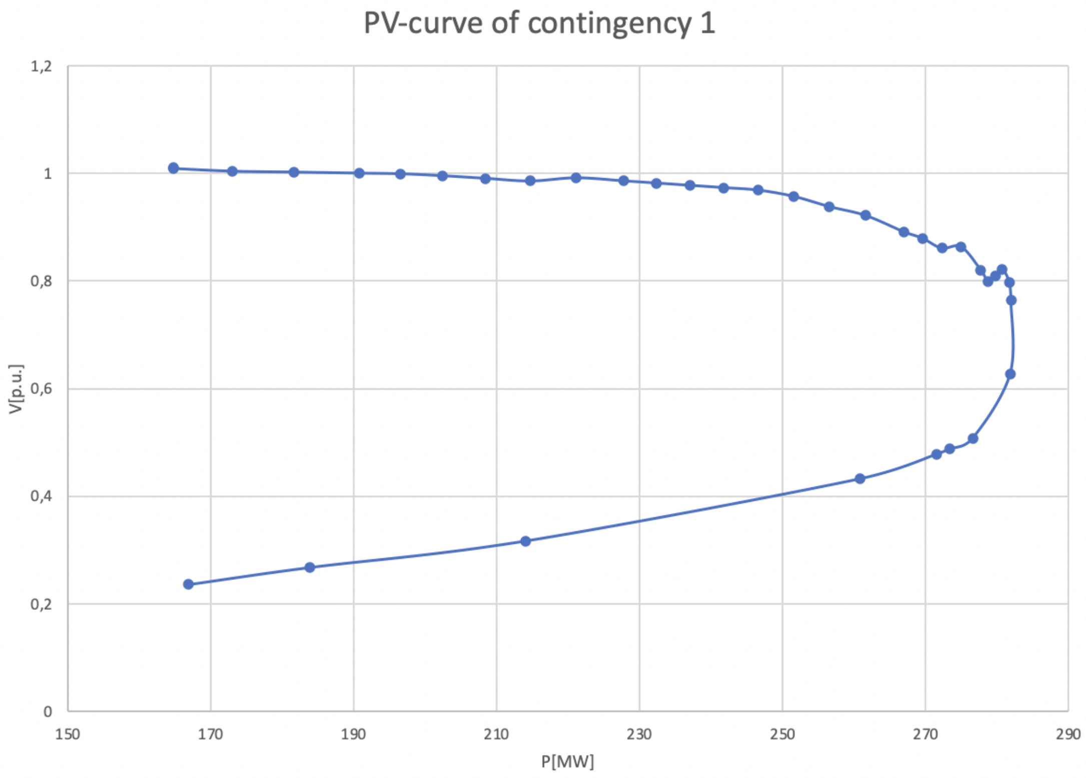


Figure 6.1: The PV curve for the first contingency simulation, where one of the parallel lines out in Lofoten is tripped. The voltage of one of the buses in the area is monitored.

peak was reached. In addition, several transmission lines reached full capacity before the voltage collapse occurred.

Figure 6.3 shows the PV curve of a bus where the line tripping is performed further out in the Lofoten archipelago. As shown, the maximum loadability in this area was 205 MW, significantly lower than in the previous two situations.

Finally, Figure 6.4 shows the dynamic simulation, where the voltages at the two buses are plotted as a function of time. A line tripping was introduced after 1 second, and the load in the area was simultaneously increased. The voltages dropped from 1.05 p.u. to 0.4 p.u. where they stabilized.

The next chapter will discuss different methods of analyzing, detecting and preventing the types of voltage collapses seen in this chapter.

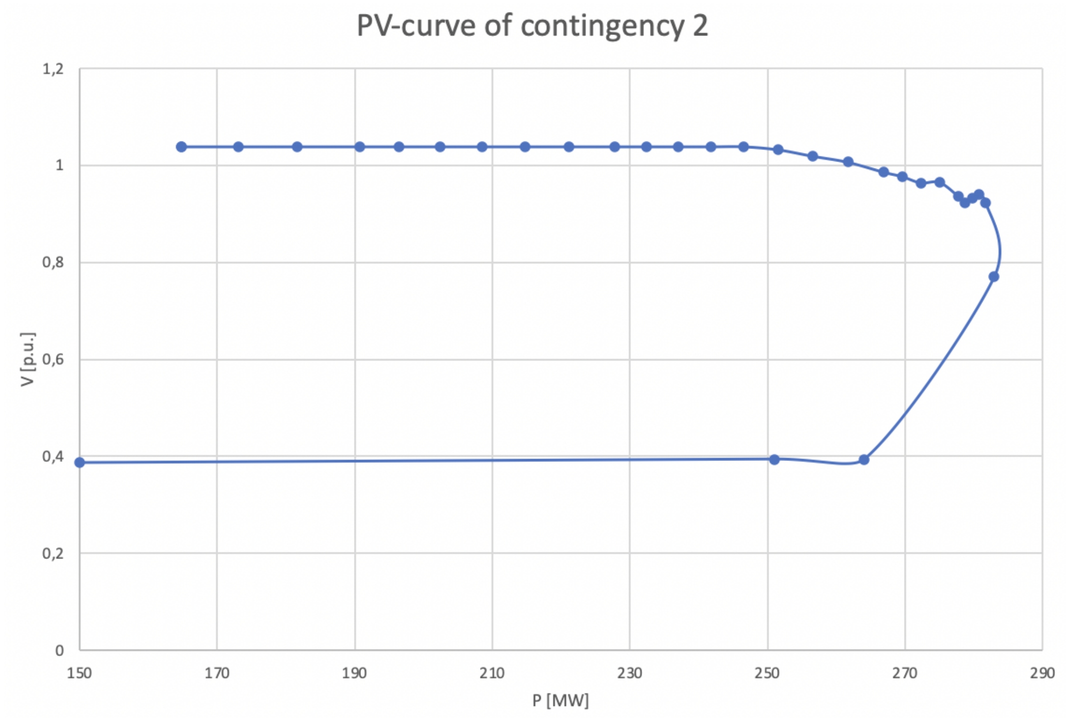


Figure 6.2: The PV curve for the second contingency simulation, where the same line as in Contingency 1 is tripped, and the voltage at another bus is monitored.

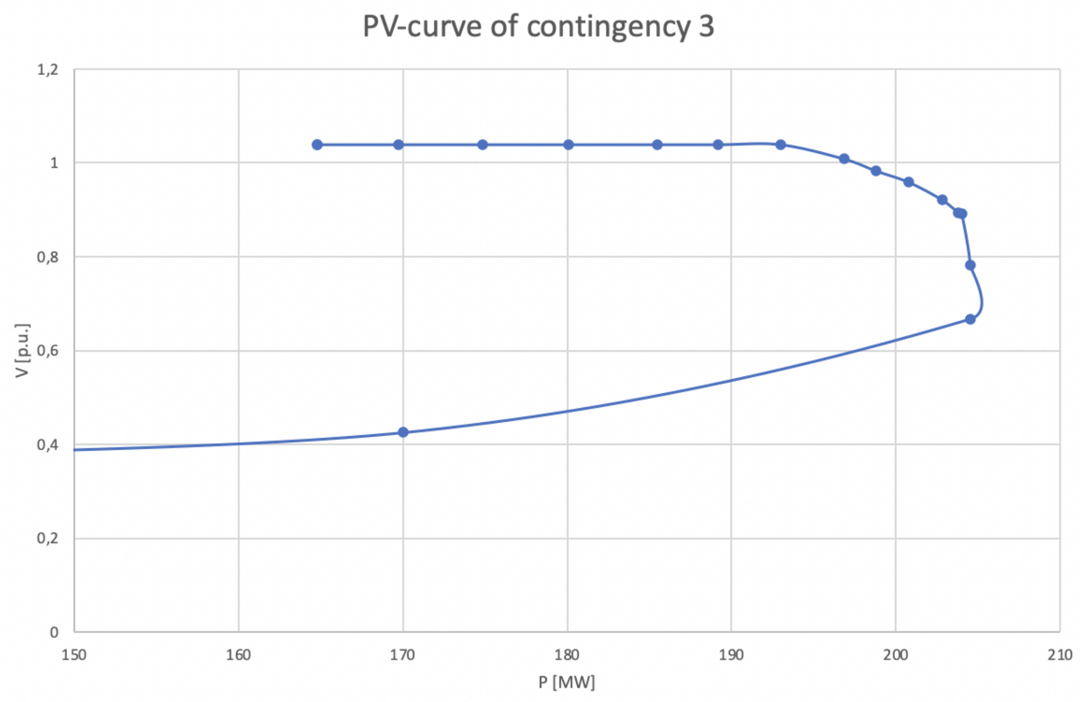


Figure 6.3: The PV curve for the third contingency simulation, where a line further out in the Lofoten archipelago is tripped. The same bus as in Contingency 2 is monitored, to see how the different line trippings result in different maximum loadability.

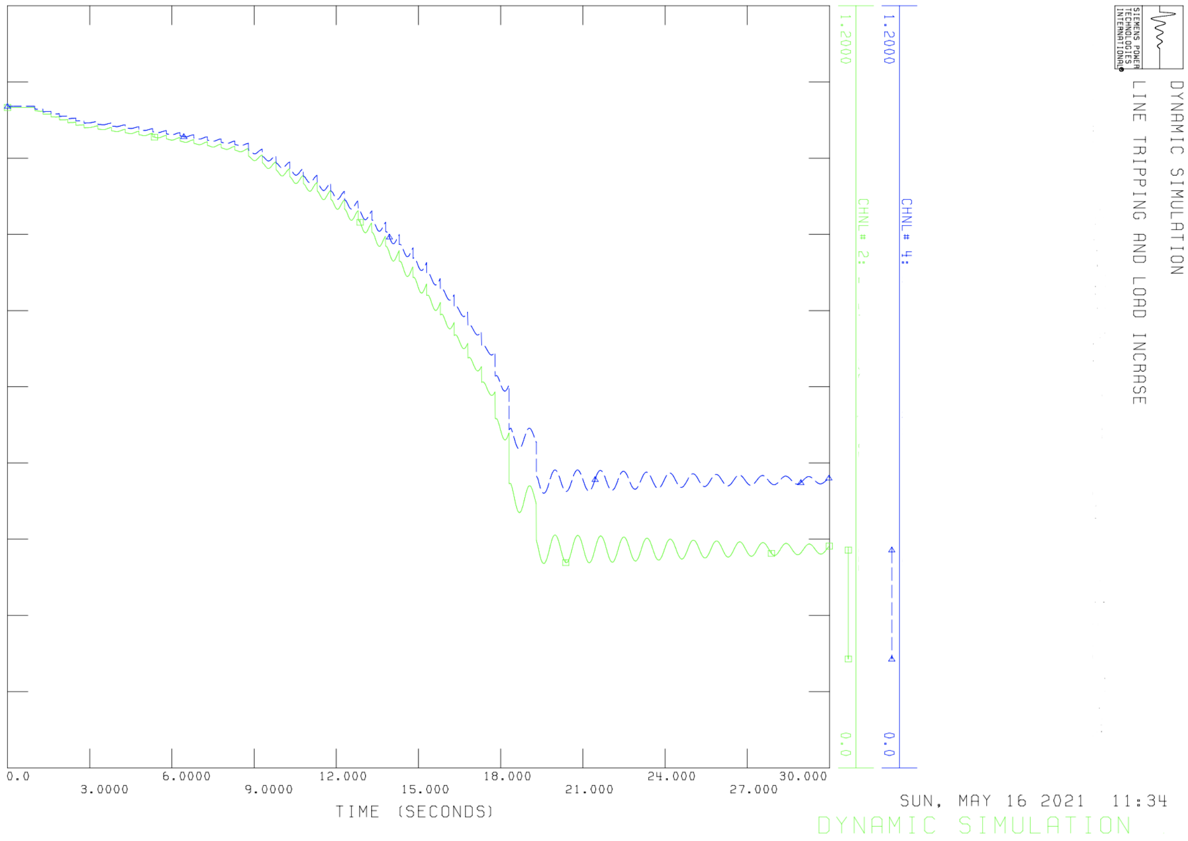


Figure 6.4: A dynamic simulation of a contingency similar to the ones above. Here, the voltages at the two buses are plotted as a function of time, showing how the system corresponds over time when a line is tripped and the load increases in the area. The values of the y-axis is in p.u.

7. Relevant Detection and Prevention Methods

7.1 Thévenin Equivalent

This section is based on the following two articles: “Dynamic Thévenin equivalent and reduced network models for PMU-based power system voltage stability analysis” by Bidadfar, Hooshyar and Vanfretti in 2018 [39] and “Real-time voltage stability assessment method for the Korean power system based on estimation of Thévenin equivalent impedance”, written by Lee and Han in 2019 [40]. Other articles with similar methods were also studied, such as [41] and [42]. However, the two aforementioned methods were chosen due to their recentness and somewhat more straightforward theory.

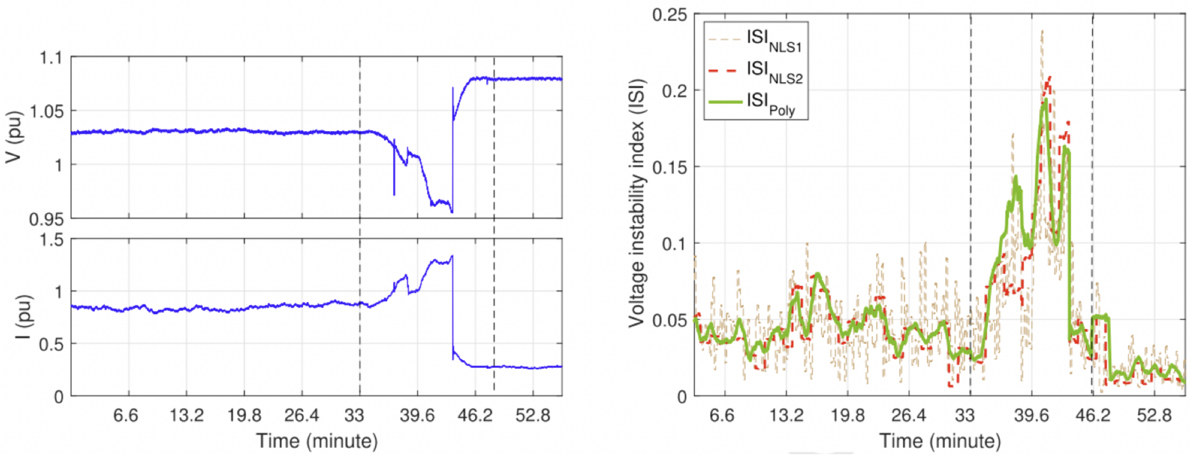
Both articles propose methods of calculating the Thévenin Equivalent (TE) from PMU data for real-time voltage stability assessment. A TE model is a way of representing a power system using a circuit as seen from an individual load bus. Usually, the model is very similar to Figure 5.2, which was presented earlier. In this figure, the voltage source represents the rest of the system. The reason to use a TE model is to simplify the system, which makes it easier to evaluate the degree of voltage stability.

The use of a TE model to calculate voltage instability has been widely used in voltage stability analyses. [39] discusses a challenge with the typical TE models, namely that the model assumes constant generation and load at all other buses while the measurements are taken. However, this is not the case, as load-changes at other buses affect the voltage at the TE model. Therefore, the authors propose a dynamic TE impedance, which will vary with changes in loads or generation. To calculate this TE impedance, a polynomial interpolation method is proposed. This method can take into account the effect of variations of other loads. The article provides a more thorough description of the model itself.

The method can be used to calculate a voltage instability index (ISI), which describes how stable the system is at any given time. When maximum loadability is reached, the system load is equal to the Thévenin impedance. Consequently,

- ISI = 0: completely stable
- ISI = 1: completely unstable.

If the load increases further after the ISI has reached a value of 1, voltage collapse may occur [41]. There are many ways of calculating the Thévenin impedance, and the proposed method in this article is one of them. To evaluate the method, it is tested on a real event in the northern part of the Nordic grid. On January 29, 2010, the grid experienced a contingency that nearly caused a voltage collapse at one of the buses. Figure 7.1 (a) shows the PMU measurements taken during the event, and how the bus voltage and current are affected. Figure 7.1 (b) shows the calculation of the ISI using two earlier models and with the polynomial interpolation method.



(a) (b)

Figure 7.1: PMU measurements at a bus in the norhtern Nordic power system (a), along with calculation of the ISI from several methods (b), including the proposed polynomial interpolation method (green). Reused with permission.

In addition, the polynomial interpolation method is tested on the Nordic 32-bus dynamic model, which is a quite large and complex system. Both in the real-life example and on the Nordic 32-bus model, the method is able to detect voltage instability fairly early, while at the same time quantify the effect the contingency had on other buses.

Similar to [39], [40] mentions the inaccuracy of assuming that the loads and generations at other buses are constant when analyzing a TE circuit during a contingency. In this article, however, the authors propose to calculate the voltage stability margin (VSM) using the TE circuit. Applying the PV curves from the previous chapter, the VSM can be calculated by comparing the operation point and the "nose-tip". A shorter distance from the operation point to the "nose-tip" indicates a lower VSM. Nevertheless, calculating the VSM as such assumes constant power components. To obtain a more accurate calculation, the article proposes an algorithm to make the simulation system closer to the actual system, shown in Figure 7.2. Using the impedance-current-power (ZIP) model which takes into consideration that the power components are non-constant, the VSM can be calculated from the PV curve, shown in Figure 7.3. The ISI can then be calculated to indicate the overall stability of the system.

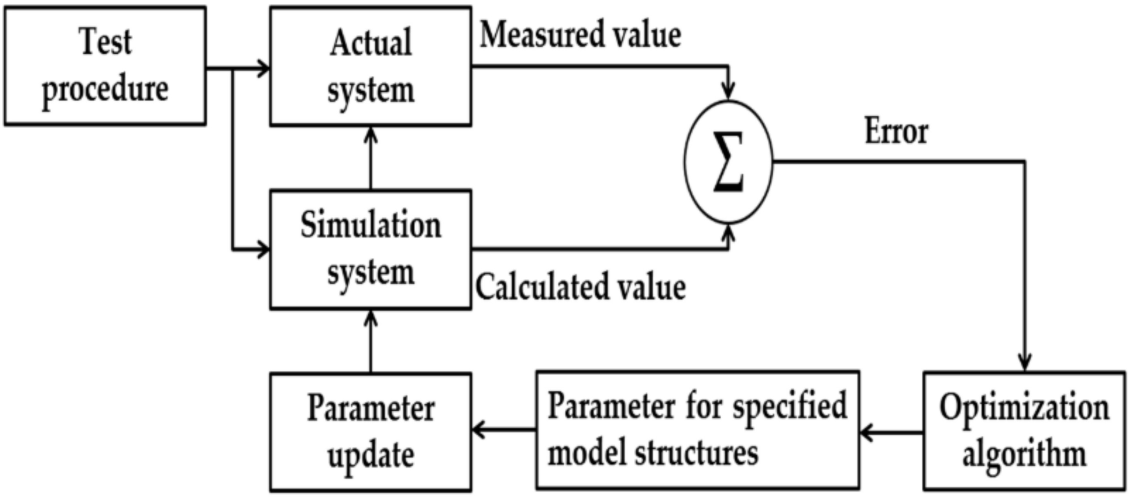


Figure 7.2: The proposed measurement-based load modeling algorithm from [40]. The goal is to minimize the calculated error between simulation and the actual system. Figure retrieved from [40] with permission.

The proposed method is tested on the Korean power grid. It is tested on two cases, where line tripping and increase of reactive power demand are simulated. In both cases, one somewhat severe and one very severe, the proposed method manages to calculate the VSM and ISI, which can be very helpful for system operators in critical situations.

7.1.1 Discussion

In summary, both methods show great potential and are suitable for online analysis based on the short calculation time. They also do not require any installations or implementations into the physical power system, except for the requirement that PMUs are installed at some buses. In many power systems, including the Nordic, this is already the case. However, [40] assumes that PMUs are installed at both the sending and receiving end of all the relevant buses, which is not always the case. [39] has taken into account that there might not be PMUs installed at every bus, and is, therefore, the more versatile model. Also, in [40], the method was tested on the Korean power grid, which has other characteristics than the Nordic. Therefore, tests on a system more similar to the Nordic power grid should be done to evaluate the model's versatility. Generally, using TE to analyze voltage stability has been thoroughly researched and tested on many different systems. Nordic TSOs are also actively researching these methods. Overall, they can be

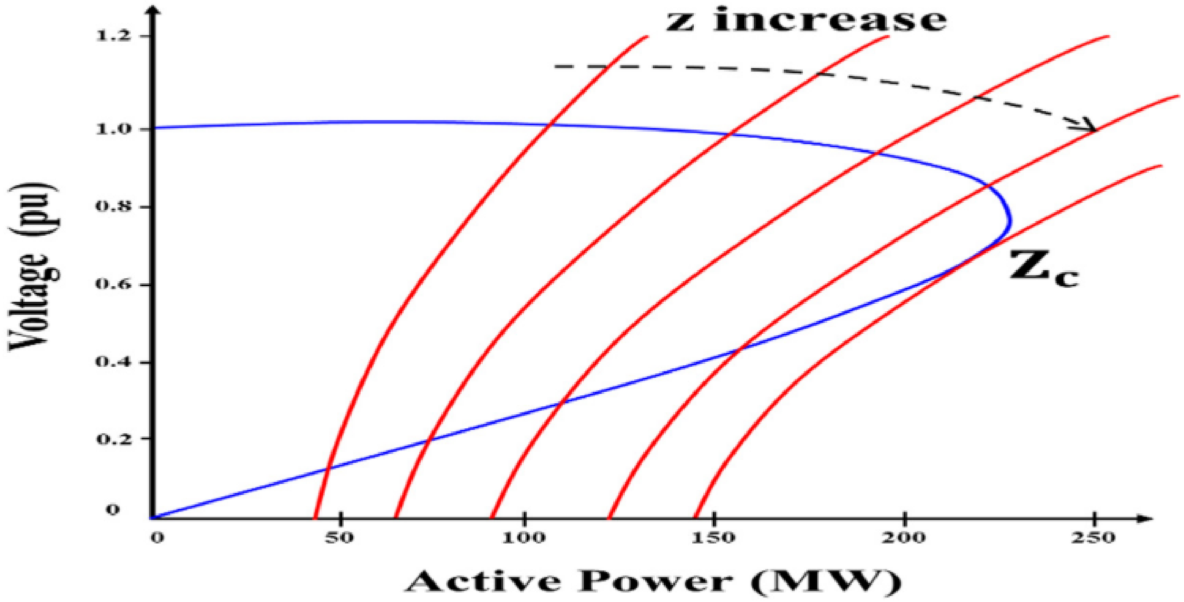


Figure 7.3: PV curve with the ZIP-model where the power components are not constant. Z_c indicates the point where the system exhibits voltage instability. Figure retrieved from [40] with permission.

considered TRL 4 or TRL 5.

7.2 Machine Learning Methods

Another prominent method of determining voltage stability in the system using PMUs is through various Machine Learning (ML) models. Generally, this topic has been extensively researched, such as in [43], [44] and [45]. Here, two different ML methods are studied, which were chosen due to their high accuracy and straightforward implementation. Shah and Verma propose in their article "PMU-ANN based approach for real time voltage stability monitoring" from 2016 an artificial neural network to monitor voltage stability [46]. The method involves utilizing a Feed Forward Neural Network (FFNN), as illustrated in Figure 7.4. This type of network contains hidden layers which consist of weights. As the model is trained on already existing data, the weights are updated to give predictions with the least amount of error. New, unseen data can then be fed into the network, and the network will attempt to predict a certain output. Here, PMU data containing voltage magnitudes and angles are fed into the network. Different FFNNs compute different voltage stability indices, which are the outputs of the models. [47] provides a more detailed description of FFNN along with other ML methods used in power system analysis.

The model is trained beforehand, and can then be implemented into an online system

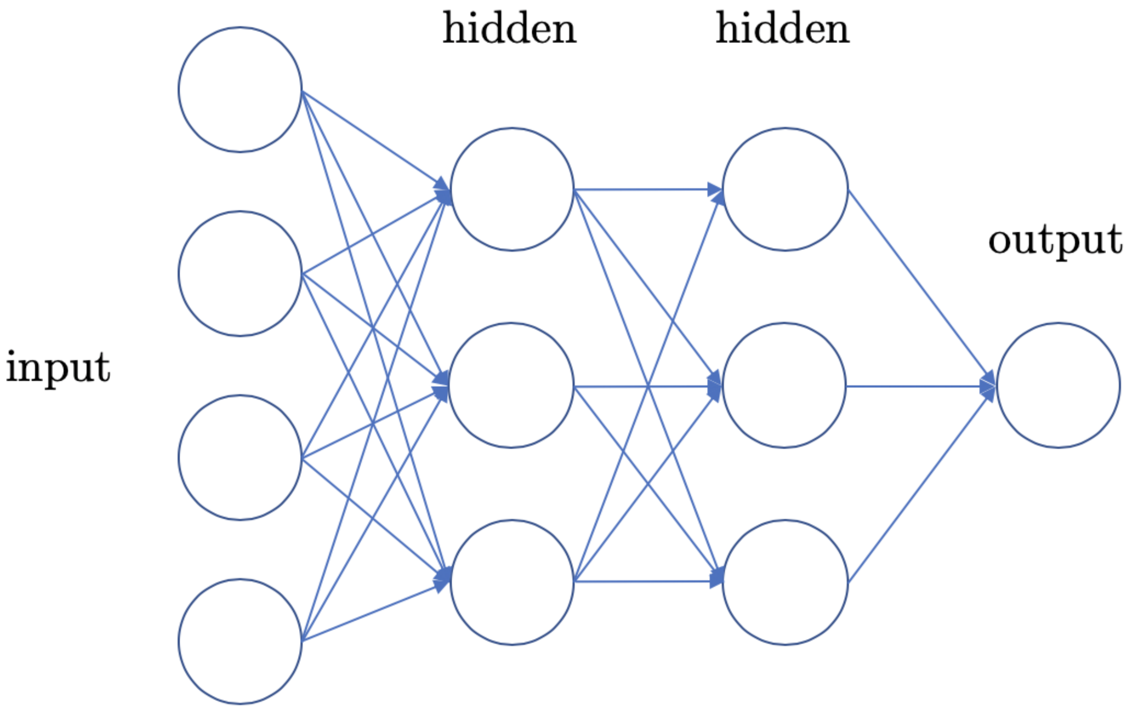


Figure 7.4: An illustration of a feed-forward neural network. Training data is fed into the model as input, and the hidden layers try to find a combination of weights which minimizes the error and most accurately computes the different ISIs. When the model is introduced to new data, it tries to predict the ISI, which will assist power system operators in decision making.

to analyze the power real-time system state. To evaluate the model, it is tested on the New England 39-bus system, which consists of 39 buses and 46 branches. Here, PMUs are located at nine different locations, which have been strategically placed to provide maximum visibility with as few PMUs as possible. The results of the simulation indicate that the model accurately determines the degree of voltage stability, and the computational time is in the order of microseconds. The model is therefore very suitable for online applications.

Vanfretti and Arava discuss in their article “Decision tree-based classification of multiple operating conditions for power system voltage stability assessment” from 2020 [48] a method of classifying voltage stability using decision trees. A decision tree is a type of supervised machine learning that tries to separate attributes into different categories. The categories are sorted into nodes as shown in Figure 7.5 based on yes/no questions which are trained on existing data. When new data is analyzed, the same yes/no questions are asked to attempt to place the data into the correct category (leaf node). An example of such a question can be: “Is the minimum voltage above 0.95 p.u.?”. Multiple questions will be asked until each data point is placed into a leaf node.

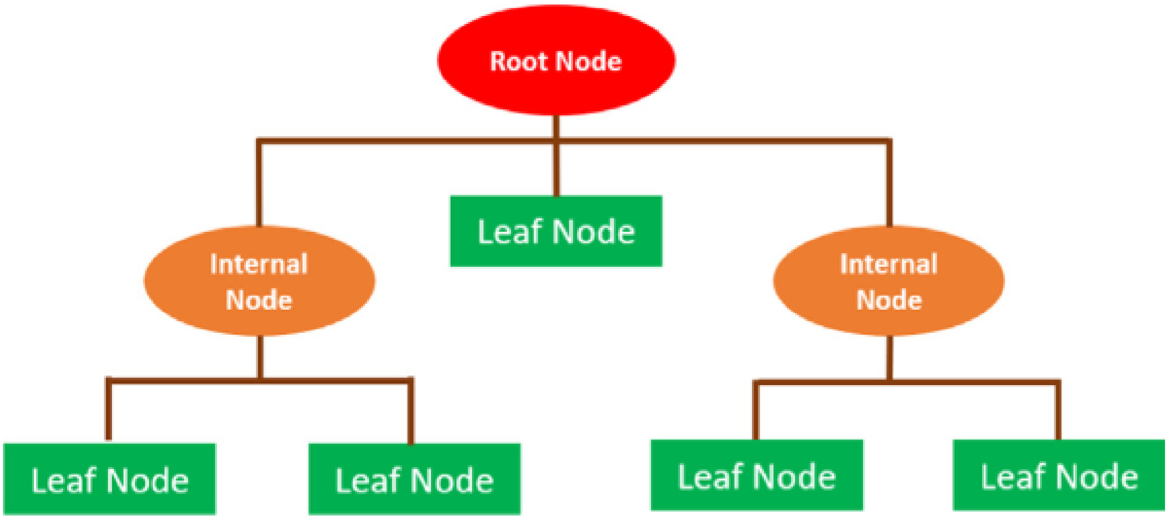


Figure 7.5: Schematic view of a typical decision tree. The leaf nodes are the final node, and a classification is made here. The internal nodes separate data into different nodes depending on certain predetermined characteristics. Reused with permission.

The article suggests to split the data points into four leaf nodes:

- Stable within grid limits
- Stable outside grid limits
- Marginally stable
- Unstable

which is also shown in Figure 7.6, along with the criteria for each node. In some previous literature, the system is either classified as “stable” or “unstable”. The authors argue that if the system is operating in the boundary of these two regions, it is likely that some operating points will be misclassified. Four classifications result in a more broad and generalized operating region. The classifications are split based on the minimum voltage at the buses, as well as the “margin”. The margin describes the distance from the nearest unstable point for all buses and is given as a percentage. The higher the percentage point, the further away the buses are from an unstable operating point.

The method is tested both on a smaller system, as well as KTH Nordic 32 bus test system, which is a larger and more complex system. Results show that the model accurately predicts the correct state with 99 % accuracy, where the incorrect predictions are in the boundary regions. By increasing the number of training samples in the boundary regions, the accuracy can increase even further.

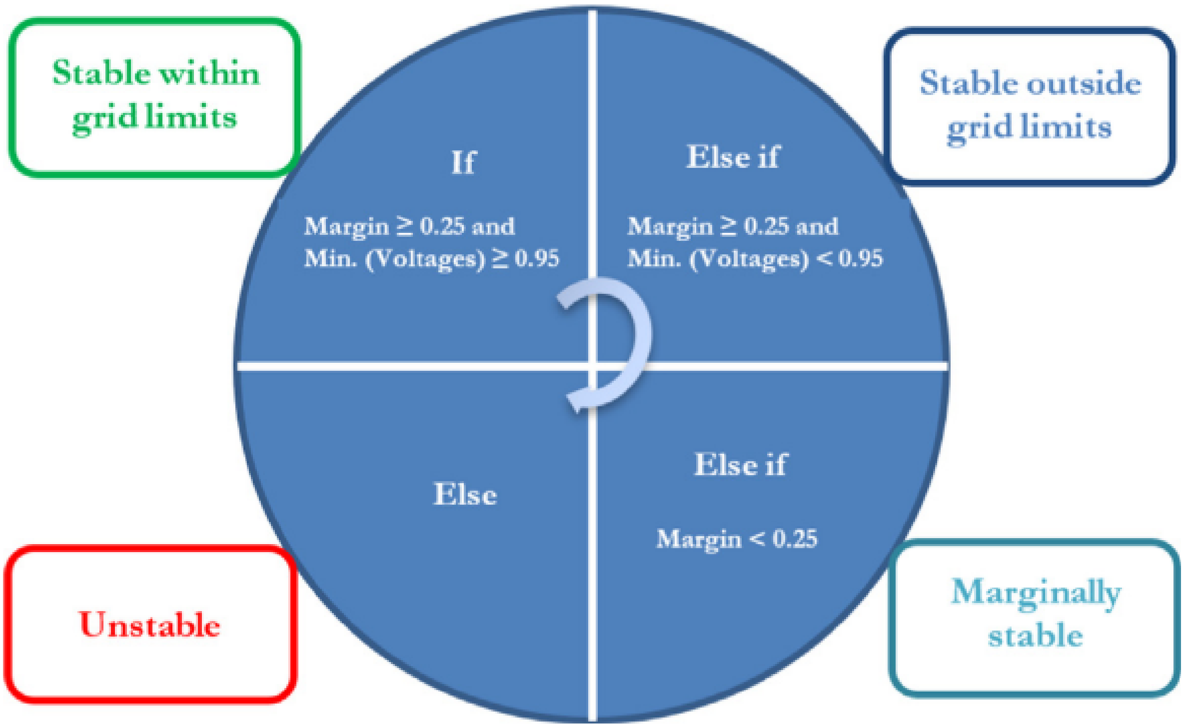


Figure 7.6: The four proposed classifications based on certain criteria. The decision tree will use training data to learn how to classify operating points, and then classify new data. Reused with permission.

7.2.1 Discussion

Generally, machine learning methods are well researched and somewhat implemented in power systems. Statnett has already finished the Impala project, which is designed to predict changes and imbalances in the power system. The findings from the project are now being implemented as part of the Nordic Balancing model [49]. Therefore, some machine learning models can be considered a TRL of 5 or 6. On the other side, the use of machine learning to analyze voltage stability is not as widely used in the industry. Here, a better estimate is TRL 4. Implementing a machine learning model like the ones mentioned above requires a myriad of data to be trained on. In the Nordic power grid, there are limitations to the number of voltage collapses, which might be a problem if the models are to be trained on real-life Nordic data. The models will also be limited by the fact that there could be many unpredicted events [50]. It is very challenging to create a model which can consider all these events.

7.3 Risk Matrix

A traditional power system is monitored using a deterministic model. Here, there are predefined limits of operation, and the system is regarded as unstable if the measured values exceed these limits. [51] points out that a deterministic model does no longer perform as well as earlier due to the increased complexity and stress of today's power systems. Consequently, more research on the opposing probabilistic method has been carried out, such as in [52] and [53]. This method monitors the power system stability based on risk, which according to [51] can be computed as a product of the probability Pr and the severity Sev of a contingency E_i. Hence, the risk of voltage collapse VC can be expressed as the sum of all these individual risks:

$$Risk(VC) = \sum_{i=1}^{M} Pr(E_i) \times Sev(E_i) \tag{7.1}$$

A risk matrix can thereafter be made, where the overall risk of a voltage collapse can be sorted into different categories, shown in Figure 7.7. In [51], a simulation was carried out where weather data was generated, and the system load level was incrementally increased. A conservative method was then compared to the proposed risk matrix method. The results indicate that the proposed method more accurately classified the risk of voltage collapse, whilst also providing system operators with a more comprehensive overview of the system.

7.3.1 Discussion

A risk matrix like this is easy for a system operator to understand, but more research needs to be done before it can be properly implemented in control centers. An inaccurate or incorrect risk assessment could result in the wrong decisions being made by the system operators, and it is therefore important that the system is rigorously tested. Currently, these types of methods for assessing voltage stability are still in the research phase, with a TRL of approximately level 2 or level 3.

7.4 Energy Storage Systems

With a higher share of intermittent renewable energy in the power sector, energy storage has gained a more widespread position. When electricity generation is higher than the consumption, which is often accredited to wind or solar power, the excess electricity could either be exported or stored. Storing the energy allows the electricity supply to be moved to a time where it is more necessary. This also helps to decrease the electricity price variations.

In recent years, articles such as [54], [55] and [56] have also investigated the use of Energy Storage Systems (ESS) in voltage stability analysis. In [56], ESS is proposed as a way of improving the ST-VS in the power system. As mentioned earlier, one of the driving forces

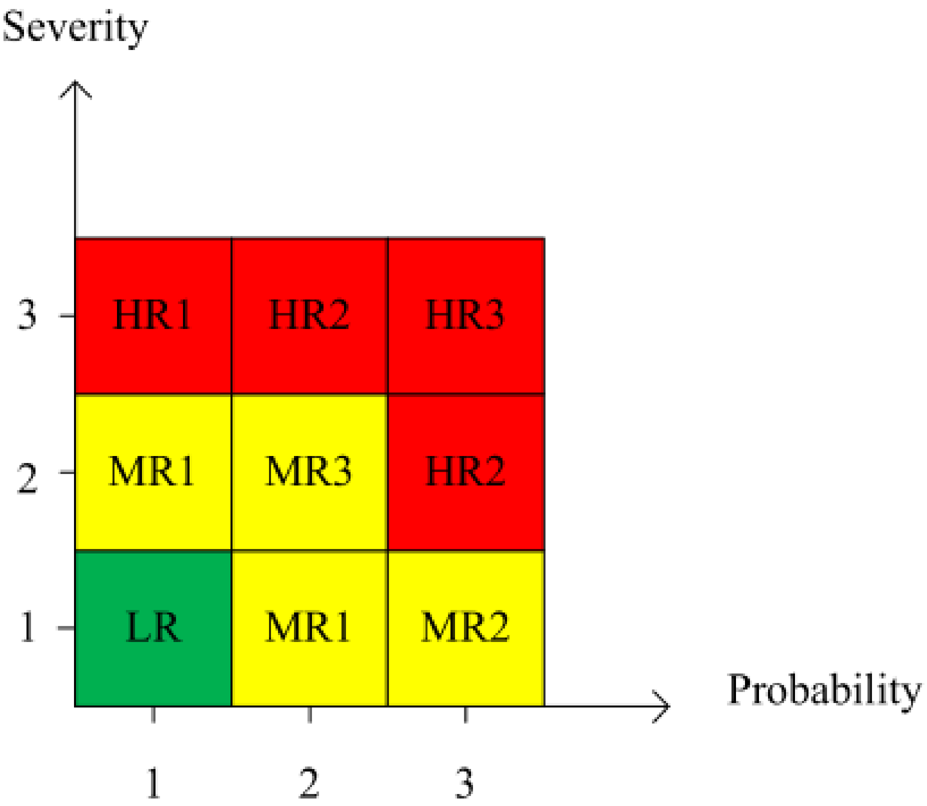


Figure 7.7: Proposed risk matrix from [51], used to determine the risk of voltage collapse. The green area poses the lowest risk, yellow poses medium risk while red poses the highest risk. Reused with permission.

of voltage instability is the lack of reactive power support. The authors point out that induction motors form a significant share of the modern power system, as much as 50 % in some cases. These induction motors can draw high amounts of reactive power if they stall, and pose a serious threat to ST-VS. New advancements in ESS technology make it possible to regulate active and reactive power independently of one another. This means that ESS can function as a method of providing reactive power support if the system experiences a decrease in voltage due to insufficient reactive power.

The method is tested by installing an ESS on bus 30 in the IEEE 30-bus test system, as shown in Figure 7.8. To challenge the voltage stability and evaluate the method, the load is increased by 60 % compared to normal operating conditions. This results in a fault in the transmission line between buses 27 and 28. Different use cases of the ESS are tried in different cases. The best results are achieved when the ESS has fault ride through and time overload capabilities. This allows the system to start power injection immediately after the fault occurs, and the transient current capability is higher than the continuous current capability. The test shows a significant increase in the ST-VS.

Similarly, [55] found that ESS can significantly improve voltage stability. In this article,

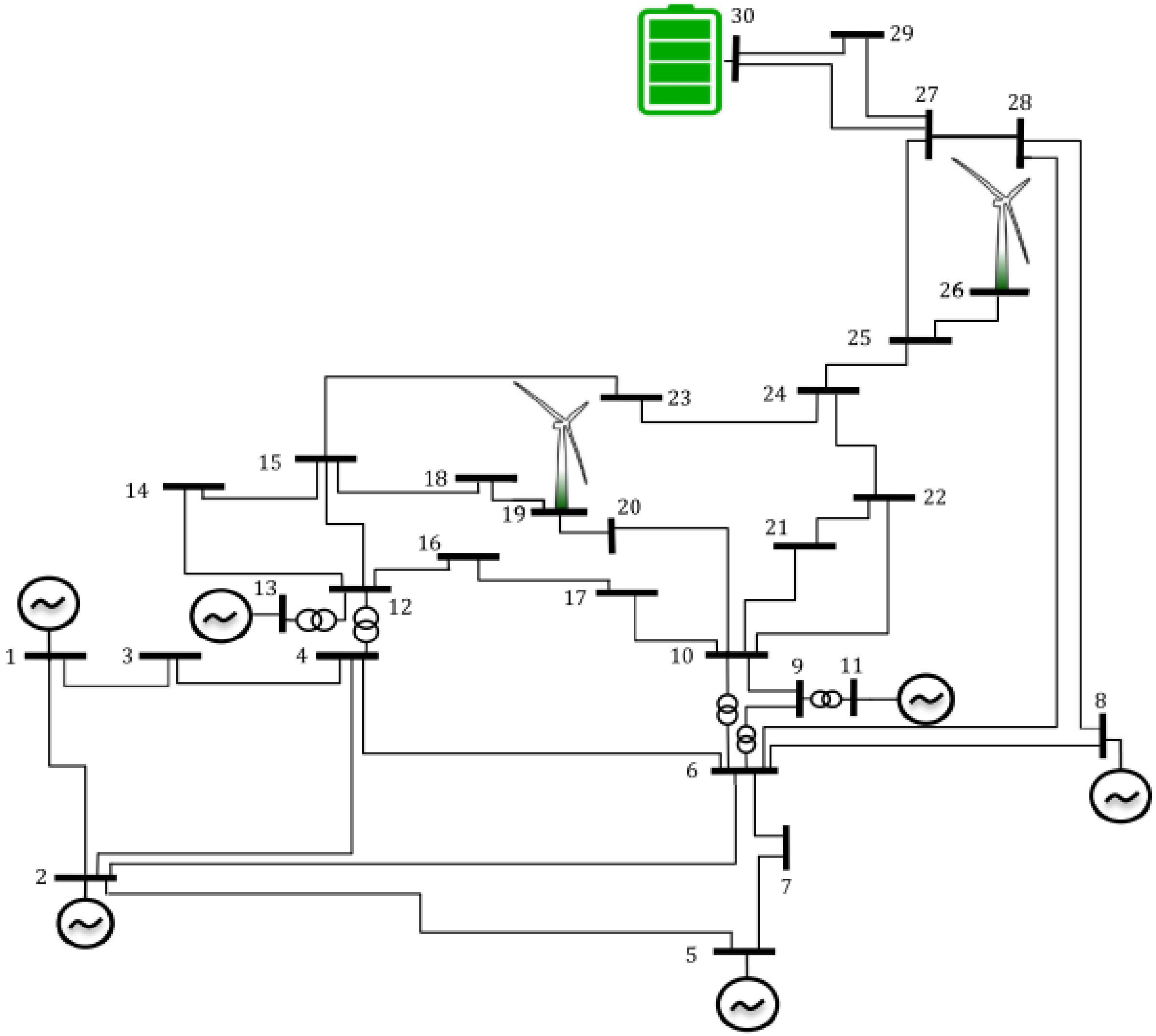


Figure 7.8: IEEE 30-bus test power system. The ESS is connected to bus 30, which is considered the weakest bus in the system. The bold line between buses 27 and 28 represent the transmission line where the fault occurs in the test cases. Reused with permission.

the focus is on optimal sizing and placement of ESS in a power system with a large share of wind power. By using a risk-based approach, the size and thereby the cost of ESS in the power system was notably reduced, while still maintaining a required level of VSM.

7.4.1 Discussion

The use of ESS in power systems provides many opportunities. The increased intermittency of some renewable energy sources might require TSOs to install more ESS in the years to come, in order to reduce bottlenecks and flatten out the daily power consumption curve. If so, they can also be used for voltage instability prevention. However, the use of ESS in voltage stability is still at a very early stage, somewhere in the TRL 2-phase.

More research has to be done before a proper prototype can be tested. Also, it requires a physical installation of ESS, which might be more costly than some of the other mentioned methods.

8. Discussion

In this chapter, the case study simulations, as well as the researched methods for voltage instability detection and prevention will be discussed. Discussions regarding the latter have also been done in Chapter 7. Thus, the different methods will be summarized and compared here, and any loose ends will be attempted to be tied up.

8.1 Case Study Discussion

As shown in the figures in Chapter 6, the PV curves from the case study had a very similar shape to the PV curve presented in Chapter 5. For the first two contingency situations, the voltage remained quite stable from the initial power demand at 165 MW to approximately 240 MW. After this, the decline in voltage was more apparent. After reaching the maximum loadability point of about 280 MW, the voltage quickly dropped and collapsed. This is indicated by the relatively fewer data points on the lower part of the curve and the steeper slope. As a result, fitting more data points on the lower part of the PV curve was a challenge. This was somewhat expected based on the background theory of PV curves. As shown from the Excel sheets in Appendix B, even tiny increments of increase in power around the voltage collapse did not help in gaining many data points in the lower half of the curve.

For Contingency 3, where the line further out in Lofoten was tripped, the PV curve had a very similar shape to the two others. However, as expected, the maximum loadability was notably lower, around 205 MW. As mentioned in Chapter 6, power to the monitored bus had to be allocated to power lines with less capacity. This severely stressed the grid, and several lines around this area quickly reached their maximum capacity. As a result, the voltage at the monitored bus was unable to stay stable as long as in the previous contingencies. It also indicates that this line is quite important to maintain voltage stability. Hence, a line tripping here along with an increased power demand in a real situation might cause a blackout unless proper action is taken in time. This is an issue that Statnett should look further into.

Although the three PV curves had a similar shape to Figure 5.4 presented in Chapter

7, Contingencies 2 and 3 seemed to stabilize at approximately 0.4 p.u., shown in Figure 6.2 and Figure 6.3. This was unexpected, as voltage stability theory suggested that the voltage would drop to 0. and have a steeper slope at this level. Further testing showed that Bus 1 from Contingency 1 eventually dropped to 0 p.u., while Bus 2 never completely collapsed. This might indicate that the bus is more voltage-dependent than Bus 1. In these cases, there is an equilibrium at low voltages in the simulation model. Furthermore, a situation like this is also possible in the physical power system.

In the three aforementioned contingencies, several lines reached full capacity before voltage collapse occurred. Transmission capacity should, therefore, also be a concern when planning future system operation. Although not particularly discussed in this thesis, upgrades to transmission lines should be of utmost importance, to avoid overcapacity.

In the dynamic simulation, the voltages at the two buses gradually collapsed after the line tripping and load increase were introduced. As the previous contingencies suggest, the voltage at the first bus (marked in green in Figure 6.4) dropped further, to 0.35 p.u. The other bus (marked in blue) stabilized at approximately 0.45 p.u. Hence, the plot fits well with the PV curves in Chapter 6. However, the voltages dropped further in the first contingencies compared to the dynamic simulation. A reason for this might be that the test system used in the dynamic simulation was slightly different from the one used in the other simulations. For a dynamic simulation, a .dyr-file is needed. This file did not exist for the test system used in the first three simulations. Nevertheless, the results indicate a similar voltage collapse.

After the voltage collapse, the voltages at the two buses oscillate before eventually stabilizing. This trend was not present in the PV curves. A reason for this might be that the dynamic simulation can continuously monitor the voltages, while the author of this thesis had to manually register the voltages for the first three contingencies. It was, therefore, more challenging to capture all the small voltage changes after the voltage collapse.

An important note to make is that the gradual increase in load in the dynamic simulation required a time interval input from the user. Hence, the plot might not completely correspond to a real-life event. However, an attempt was made to create a realistic scenario. Because a slightly different model was used for the dynamic simulation, the maximum loadability point was also somewhat higher than in the first contingencies.

8.2 Detection and Prevention Methods Discussion

Chapter 7 discussed several different methods to detect voltage instability and mitigate the risk of voltage collapse. These methods all show potential, but not all are equally realistic to implement. Of the four methods, the use of risk matrices and ESS are considered the least promising, at least for the near future. Implementing a method to be used for online assessment in control rooms requires a great deal of testing and the method must be very accurate. These two methods are far from this stage. Machine learning methods, conversely, have been significantly more tested and researched in the power system field. Several different methods are either already in use, or at a late stage in development. However, the use of ML in voltage stability analysis is somewhat limited. Despite this, the improvement of ML in the last years indicates that it will likely be researched and developed more in the area of voltage stability analysis in the coming years.

Lastly, the TE model has been extensively researched, also with the Nordic power system in mind, and is considered to have the highest TRL. In addition to the methods discussed in Chapter 7, there is a myriad of articles discussing and using the TE method. Therefore, it might be feasible to try to integrate this into the NEWEPS project. Of the two TE methods investigated, the dynamic TE model presented in [39] is most promising, as it has already been tested on a real-life event in the Nordic power system. However, there have not been performed any real-time tests using this model. In addition, it is unclear how system operators will use this method along with their current operation. Among other details, visualization of the dynamic TE model in the control room will have to be assessed. Also, economic and practical details regarding the implementation have to be examined.

Furthermore, system operators are dependent on the analysis methods they use to be highly reliable. When contingencies or other problems occur in the power system, the system operators rapidly need to address the issue and devise a solution. Therefore, there is no room for errors in the measurements or the digital system. The dynamic TE model has not yet been proven its consistency in evaluating the risk of voltage instability.

HVDC cables were briefly mentioned in Section 2.5. In the Nordic power system, there have been set limits to the ramping speed of HVDC due to voltage stability concerns. Presently, this value is 30 MW/min, while the technical limit is nearly tenfold [6]. This is another aspect that should be taken into account. Testing the dynamic TE model on a power system whilst performing an HVDC ramping can further indicate its performance and whether it is suitable for implementation in the Nordic power system.

An important prerequisite for the four methods researched is the availability of PMUs in the power system. Although the different methods have various requirements for the amount of PMUs installed, they all rely on PMU measurements to be able to continuously monitor the power system state. As shown in the results, the voltage remains quite constant until a certain load power, and then swiftly declines. Being able to quickly detect a more rapid decline in voltage is paramount to warn system operators and take action. It is, though, important to mention that the articles discussing risk matrices and

ESS do not specifically mention the use of PMUs. However, PMUs are still considered necessary to detect and prevent voltage instability early. The articles were therefore included regardless. As mentioned in Chapter 3, there are currently approximately 120 PMUs installed in the Norwegian power system and an additional 145 PMUs in the rest of the Nordic countries. According to a Statnett employee in the regional central office [57], the PMUs are mostly used in research, and not in online monitoring in the control rooms. This is partly because system operators need information about the entire power system, which the installed PMUs are not yet able to provide. Therefore, installing more PMUs in the next years is necessary if they are to be used for online analysis.

Another challenge with PMUs is the amount of storage required. Because PMUs have a much higher sampling rate than the traditional RTUs, the file sizes will also be much larger. For online voltage stability analysis, the files could potentially be deleted after some time when it is no longer being used. However, for the post-contingency analyses, it might be desirable to keep data for longer periods. Unless the files are either compressed or parts of the data are deleted, storage deficiency might become a challenge.

In the course of this thesis, several priorities had to be made. Since the NEWEPS project will feature a PhD education, the goal was to set a starting point and give a general description of the challenges as well as several different methods for voltage instability detection and prevention. Therefore, it was determined that testing one of these methods on real data was superfluous. Instead, the PhD education or other research on the topic will benefit from an overview of the current challenges and state-of-the-art methods.

9. Conclusion

9.1 Conclusions

In this master's thesis, the main goal was to provide an overview of ways to mitigate the risk of voltage instability and collapse. Consequently, a description of voltage stability theory has been presented, along with several methods for detecting and preventing voltage instability. Also, this thesis has performed multiple contingency analyses to confirm the voltage stability theory and to investigate how a weaker part of the Norwegian power grid responds to these contingencies. Although there have been previous literature reviews regarding voltage stability in the past, this thesis provides a state-of-the-art summary of the methods available in 2021, and with a purely Nordic perspective.

The thesis showed that the Norwegian power grid to a large extent responded as expected; tripping a line while increasing the load in the area eventually results in a voltage collapse. The voltages at the buses changed less in the early stages of load increase but changed more as the maximum loadability approached. For the contingencies simulated in "Sørnettet", line trippings closer to the observed buses resulted in a lower maximum loadability. In all contingencies, the voltage dropped to between 0.2 and 0.4 p.u. after the voltage collapse.

Out of the four methods researched herein, the dynamic Thévenin equivalent method showed the most potential, as it was deemed the highest TRL at level 5 and might be the easiest to implement in a control room situation. Also, several papers from Sintef and NTNU have researched the use of TE models, which indicates a higher TRL in the Nordic area as well. The different machine learning methods discussed in this thesis are also promising. Generally, ML methods were considered a TRL of 5 or 6, but only TRL 4 within voltage stability. Thus, more research on ML in this area is still needed. ESS and risk matrix were considered a TRL of 2 or 3, and not relevant to implement in the nearest future.

For online voltage stability assessment to be properly implemented, there is a need for continuous real-time monitoring of the power system state. The current SCADA system measures voltage and current at buses with an insufficient time resolution, and the methods researched in this thesis require a higher sampling rate. Therefore, having a sufficient number of PMUs installed in the power system is a prerequisite for these methods to be implemented. The power system is continuously increasing in complexity, and power consumption is less predictable than before. Having a detailed and live overview of the system state is even more important than before. Data analysis using PMUs will be at the forefront of this development.

The background for this thesis was the NEWEPS project. Here, WP4 specifically deals with voltage instability detection and prevention. The goal of this thesis was, therefore, to set a starting point that can be further assessed in the project. For instance, a PhD education is expected to be completed as part of the project. Some recommendations for further work in this PhD thesis and the NEWEPS project as well as voltage stability assessment in general will be presented below.

9.2 Further Work and Recommendations

In this thesis, several methods have been researched. Of these methods, the dynamic TE method was considered most relevant and easiest to implement into the Nordic power system. As the goal was to create a starting point for further research, the following suggestions are presented to continue development in this field:

- The dynamic TE model was already tested on a real event in the Northern Nordic grid. To substantiate the performance of the model, the method should be validated on more test systems and real-life events.
- There should also be an investigation into how this method could be properly implemented into the Nordic grid. Here, communication with system operators is key so that the implemented method will be used regularly.
- In the article discussing the dynamic TE model, the authors took into account that PMUs might not be installed at all buses for the model to work. Further research is recommended regarding where and how many PMUs should be installed in the Nordic power system for the method to work properly.
- Machine learning is also promising within the field of voltage stability analysis. Tests on the Nordic power system and real-life data should be done to assess their performance.
- Although the use of risk matrices and ESS were considered a low TRL, they are still relevant concepts. Further investigation into the use of these methods should be considered.

References

[1] IPCC, “Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,” Tech. Rep., 2018.

[2] European Commission, *Going climate-neutral by 2050*, Luxembourg, 2018, DOI: 10.2834/02074.

[3] European Commission, *The European Green Deal*, Brussels, Belgium, 2019, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN.

[4] IEA-ETSAP and IRENA, “Renewable Energy Integration in Power Grids: Technology Brief,” Tech. Rep., 2015: 1–36.

[5] K. Mahmud, M. J. Hossain, and J. Ravishankar, "Peak-Load Management in Commercial Systems with Electric Vehicles", *IEEE Systems Journal*, vol. 13 (2): 1872–1882, 2019, DOI: 10.1109/JSYST.2018.2850887.

[6] Statnett SF, Svenska Kraftnät, Energinet, and Fingrid, *Nordic Early Warning Early Prevention System (NEWEPS) project description*, 2020.

[7] G. Neidhöfer, "50-Hz Frequency [History]", *IEEE Power and Energy Magazine*, vol. 9 (4): 66–81, 2011, DOI: 10.1109/mpe.2011.941165.

[8] ENTSO-E, *First Milestone of Future Synchronous Connection of the Baltic Power System with Continental Europe*, 2019, [Online]. Available: https://www.entsoe.eu/news/2019/05/29/first-milestone-of-future-synchronous-connection-of-the-baltic-power-system-with-continental-europe/ (visited on 02/24/2021).

[9] S. Berlijn, *Kraftsystemets rolle*, [Lecture note], 2021.

[10] O. S. Grande, G. Doorman, and B. H. Bakken, “Exchange of balancing resources between the Nordic synchronous system and the Netherlands / Germany / Poland,” SINTEF, Trondheim, Tech. Rep., 2008: 1–67, [Online]. Available: https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2448278.

[11] Entso-e, “Ten-Year Network Development Plan 2020 – Main Report,” Berlin, Tech. Rep., 2020, [Online]. Available: https://tyndp.entsoe.eu/.

[12] Energy Transition Commission, “Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century,” Tech. Rep., 2018, [Online]. Available: https://www.energy-transitions.org/publications/mission-possible/.

[13] Statnett SF, Fingrid, Energinet, and Svenska Kraftnät, "Challenges and Opportunities for the Nordic Power System", 2016, [Online]. Available: https://www.fingrid.fi/en/pages/news/news/2016/report-challenges-and-opportunities-for-the-nordic-power-system/.

[14] ENTSO-E, “Research, Development & Innovation Roadmap 2020-2030,” Tech. Rep., 2020.

[15] K. Uhlen, Smart Transmission Grids Operation and Control (STRONgrid), in *Sustainable Energy Systems 2050*, Trondheim, [Online]. Available: `https://www.nordicenergy.org/wp-content/uploads/2015/11/STRONgrid.pdf`.

[16] G. Yang and O. J. Oleson, “Secure Operation of Sustainable Power System (SOSPO),” Techincal University of Denmark, Lyngby, Tech. Rep., 2013, [Online]. Available: `https://www.researchgate.net/publication/283463879_Secure_operation_of_sustainable_power_system_WP1_future_scenario_description_system_in_context_and_specifications`.

[17] M. S. Thomas and J. D. McDonald, *Power System SCADA and Smart grids*, 1st ed. Florida, USA: CRC Press, 2015.

[18] M. M. Ahmed and W. L. Soo, "Supervisory control and data acquisition system (SCADA) based customized remote terminal unit (RTU) for distribution automation system", *PECon 2008 - 2008 IEEE 2nd International Power and Energy Conference*, (PECon 08): 1655–1660, 2008, DOI: `10.1109/PECON.2008.4762744`.

[19] K. Uhlen, P. Overholt, and O. Valentine, “"Synchrophasor applications for wide area monitoring and control",” Tech. Rep., 2016, [Online]. Available: `https://www.iea-isgan.org/wp-content/uploads/2018/02/ISGAN_DiscussionPaper_SynchrophasorApplications_2016-1.pdf`.

[20] 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`.

[21] H. Chappa and T. Thakur, "Voltage instability detection using synchrophasor measurements: A review", *International Transactions on Electrical Energy Systems*, vol. 30 (6): 1–34, 2020, DOI: `10.1002/2050-7038.12343`.

[22] B. Vicol, M. Gavrilas, and O. Ivanov, Modern Technologies for Power Systems Monitoring, in *ELS International Symposium*, 2013, [Online]. Available: `https://www.researchgate.net/publication/262733334_MODERN_TECHNOLOGIES_FOR_POWER_SYSTEMS_MONITORING`.

[23] S. M. Mahaei and M. T. Hagh, "Minimizing the number of PMUs and their optimal placement in power systems", *Electric Power Systems Research*, vol. 83 (1): 66–72, 2012, DOI: `10.1016/j.epsr.2011.09.010`.

[24] O. Finseth, *Questions regarding PMUs*, Ås, 2021.

[25] A. Skånlund and K. Hornnes, *R&D Gathering - PMU as Enabler for Digital Transformation*, Trondheim, 2019.

[26] Statnett SF, *Technology Readiness Level Table*, 2020.

[27] Statnett SF, “Sammendrag av samfunnsøkonomisk analyse -offisiell,” Tech. Rep., 2017, [Online]. Available: `https://www.statnett.no/globalassets/her-er-vare-prosjekter/region-nord/kvandal-kanstadbotn/vedlegg-6-sammendrag-av-samf.ok.-analyse.pdf`.

[28] Siemens Industry Inc., *Program Operation Manual PSS/E 34.6.1*, 2019.

[29] ENTSO-E, *ENTSO-E Transmission System map*, 2021, [Online]. Available: `https://www.entsoe.eu/data/map/` (visited on 04/13/2021).

[30] IEEE/CIGRE Joint Task Force, "Definition and Classification of Power System Stability", *IEEE Transactions on Power Systems*, vol. 19 (2): 1387–1401, 2004, DOI: `10.1109/TPWRS.2004.825981`.

[31] J. Machowski, Z. Lubosny, J. W. Bialek, and J. R. Bumby, *Power System Dynamics: Stability and Control*, 3rd ed. Hoboken, NJ: John Wiley & Sons, 2020.

[32] T. van Cutsem and C. Vournas, *Voltage stability of electric power systems*. Springer Science+Business Media, 2008.

[33] Statnett SF, “Årsstatistikk 2018,” Tech. Rep., 2018, [Online]. Available: `https://www.statnett.no/for-aktorer-i-kraftbransjen/systemansvaret/arsrapporter-fra-feilanalyse/`.

[34] D. T. Duong, Online Voltage Stability Monitoring and Coordinated Secondary Voltage Control, PhD thesis, NTNU, 2016.

[35] J. D. Glover, T. J. Overbye, and M. S. Sarma, *Power System Analysis & Design*, 6th ed. MA, USA: Cengage Learning, 2017.

[36] D. Q. Zhou, U. D. Annakkage, and A. D. Rajapakse, "Online monitoring of voltage stability margin using an artificial neural network", *IEEE Transactions on Power Systems*, vol. 25 (3): 1566–1574, 2010, DOI: `10.1109/TPWRS.2009.2038059`.

[37] A. K. Deb, *Powerline Ampacity System: Theory, Modeling and Applications*, First edit. Boca Raton, FL: CRC Press, 2000.

[38] S. G. Johansson, "Mitigation of Voltage Collapse caused by Armature Current Protection", *IEEE Transactions on Power Systems*, vol. 14 (2): 591–599, 1999, DOI: `10.1109/59.761885`.

[39] A. Bidadfar, H. Hooshyar, and L. Vanfretti, "Dynamic Thévenin equivalent and reduced network models for PMU-based power system voltage stability analysis", *Sustainable Energy, Grids and Networks*, vol. 1, 2018, DOI: `10.1016/j.segan.2018.07.002`.

[40] Y. Lee and S. Han, "Real-time voltage stability assessment method for the Korean power system based on estimation of Thévenin equivalent impedance", *Applied Sciences (Switzerland)*, vol. 9 (8), 2019, DOI: `10.3390/app9081671`.

[41] S. Polster, H. Renner, D. T. Duong, and K. Uhlen, "Voltage Stability Monitoring using a Modified Thevenin Impedance", *2017 IEEE Manchester PowerTech*, 2017, DOI: `10.1109/ptc.2017.7980864`.

[42] H. Y. Su and C.-W. Liu, "Estimating the Voltage Stability Margin Using PMU Measurements", *IEEE Transactions on Power Systems*, vol. 31 (4): 3221–3229, 2016, DOI: `10.1109/TPWRS.2015.2477426`.

[43] H. Yang, W. Zhang, J. Chen, and L. Wang, "PMU-based voltage stability prediction using least square support vector machine with online learning", *Electric Power Systems Research*, vol. 160: 234–242, 2018, DOI: `10.1016/j.epsr.2018.02.018`.

[44] H. Yang, R. C. Qiu, X. Shi, and X. He, "Unsupervised feature learning for online voltage stability evaluation and monitoring based on variational autoencoder", *Electric Power Systems Research*, vol. 182: 106253, 2020, DOI: `10.1016/j.epsr.2020.106253`.

[45] M. Ghalei Monfared Zanjani, K. Mazlumi, and I. Kamwa, "Combined analysis of distribution-level PMU data with transmission-level PMU for early detection of long-term voltage instability", *IET Generation, Transmission and Distribution*, vol. 13 (16): 3634–3641, 2019, DOI: `10.1049/iet-gtd.2019.0311`.

[46] H. Shah and K. Verma, "PMU-ANN based approach for real time voltage stability monitoring", *2016 IEEE 6th International Conference on Power Systems, ICPS 2016*, 2016, DOI: `10.1109/ICPES.2016.7584137`.

[47] T. Korten, "A Study of Machine Learning Methods Used as Decision Support Tool for Grid Operators – The NEWEPS Project," Master's thesis, Faculty of Science and Technology, NMBU, Ås, 2021.

[48] L. Vanfretti and V. S. N. Arava, "Decision tree-based classification of multiple operating conditions for power system voltage stability assessment", *Electrical Power and Energy Systems*, vol. 123, 2020, DOI: `10.1016/j.ijepes.2020.106251`.

[49] E. Lindeberg, *E-mail correspondence regarding the IMPALA-project*, Ås, 2021.

[50] M. Mohammadniaei, F. Namdari, and M. R. Shakarami, Voltage Collapse Detection and Prevention Based on PMUs Measurement, in *The 34th International Power System Conference*, Tehran, Iran: IEEE, 2019: 497–503, DOI: `10.1109/PSC49016.2019.9081520`.

[51] N. Aminudin, N. M. Ramli, M. Marsadek, N. M. Ramli, and T. K. Rahman, "Classification of risk of voltage collapse using risk matrix", *2016 IEEE International Conference on Power System Technology, POWERCON 2016*: 1–5, 2016, DOI: `10.1109/POWERCON.2016.7754030`.

[52] M. Ni, J. D. McCalley, V. Vittal, S. Greene, C.-W. Ten, V. S. Ganugula, and T. Tayyib, "Software Implementation of Online Risk-Based Security Assessment", *IEEE Transactions on Power Systems*, vol. 18 (3): 1165–1172, 2003, DOI: `10.1109/MPER.2002.4311833`.

[53] M. Marsadek, A. Mohamed, and Z. M. Norpiah, "Assessment and classification of line overload risk in power systems considering different types of severity functions", *WSEAS Transactions on Power Systems*, vol. 5 (3): 182–191, 2010.

[54] O. B. Adewuyi, R. Shigenobu, K. Ooya, T. Senjyu, and A. M. Howlader, "Static voltage stability improvement with battery energy storage considering optimal control of active and reactive power injection", *Electric Power Systems Research*, vol. 172: 303–312, 2019, DOI: `10.1016/j.epsr.2019.04.004`.

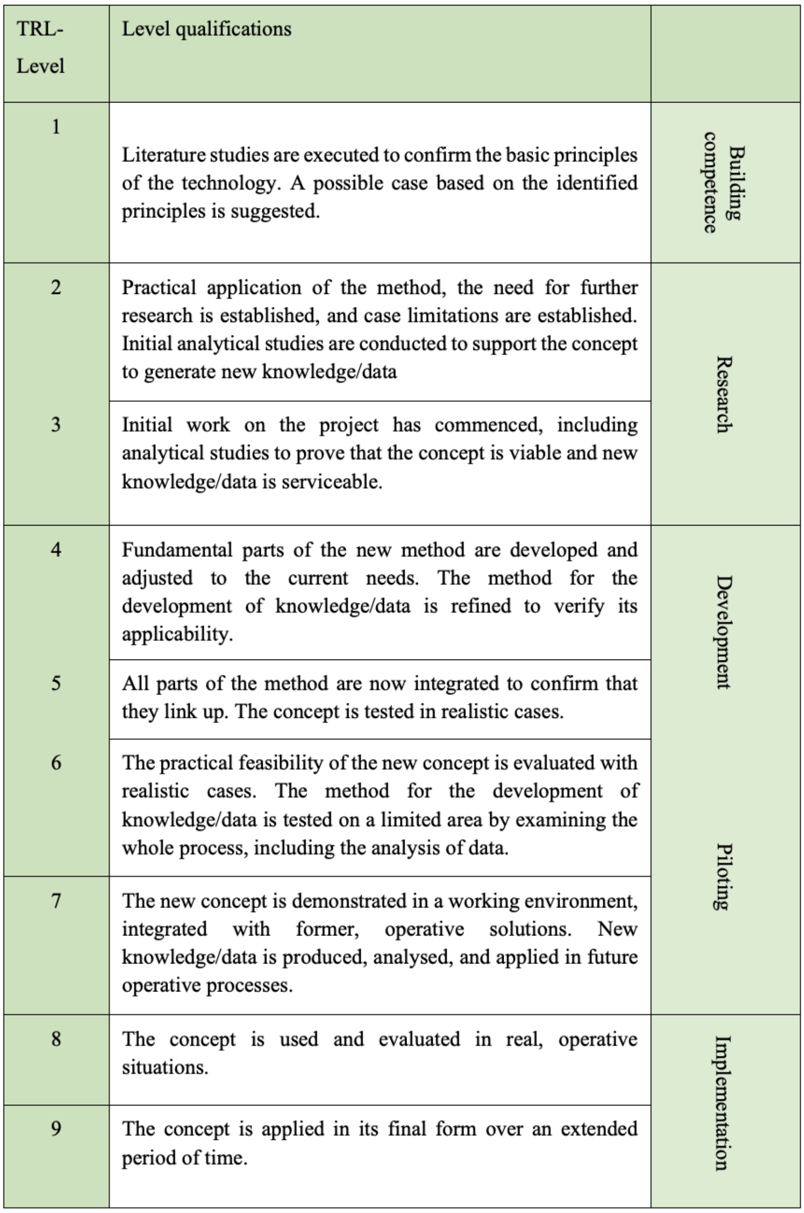
[55] A. Jalali and M. Aldeen, "Risk-Based Stochastic Allocation of ESS to Ensure Voltage Stability Margin for Distribution Systems", *IEEE Transactions on Power Systems*, vol. 34 (2): 1264–1277, 2019, DOI: `10.1109/TPWRS.2018.2873774`.

[56] A. Jalali and M. Aldeen, "Short-Term Voltage Stability Improvement via Dynamic Voltage Support Capability of ESS Devices", *IEEE Systems Journal*, vol. 13 (4), 2019, DOI: `10.1109/JSYST.2018.2882643`.

[57] G. Sætermo, *Short interview regarding voltage stability in the control room*, Ås, 2021.

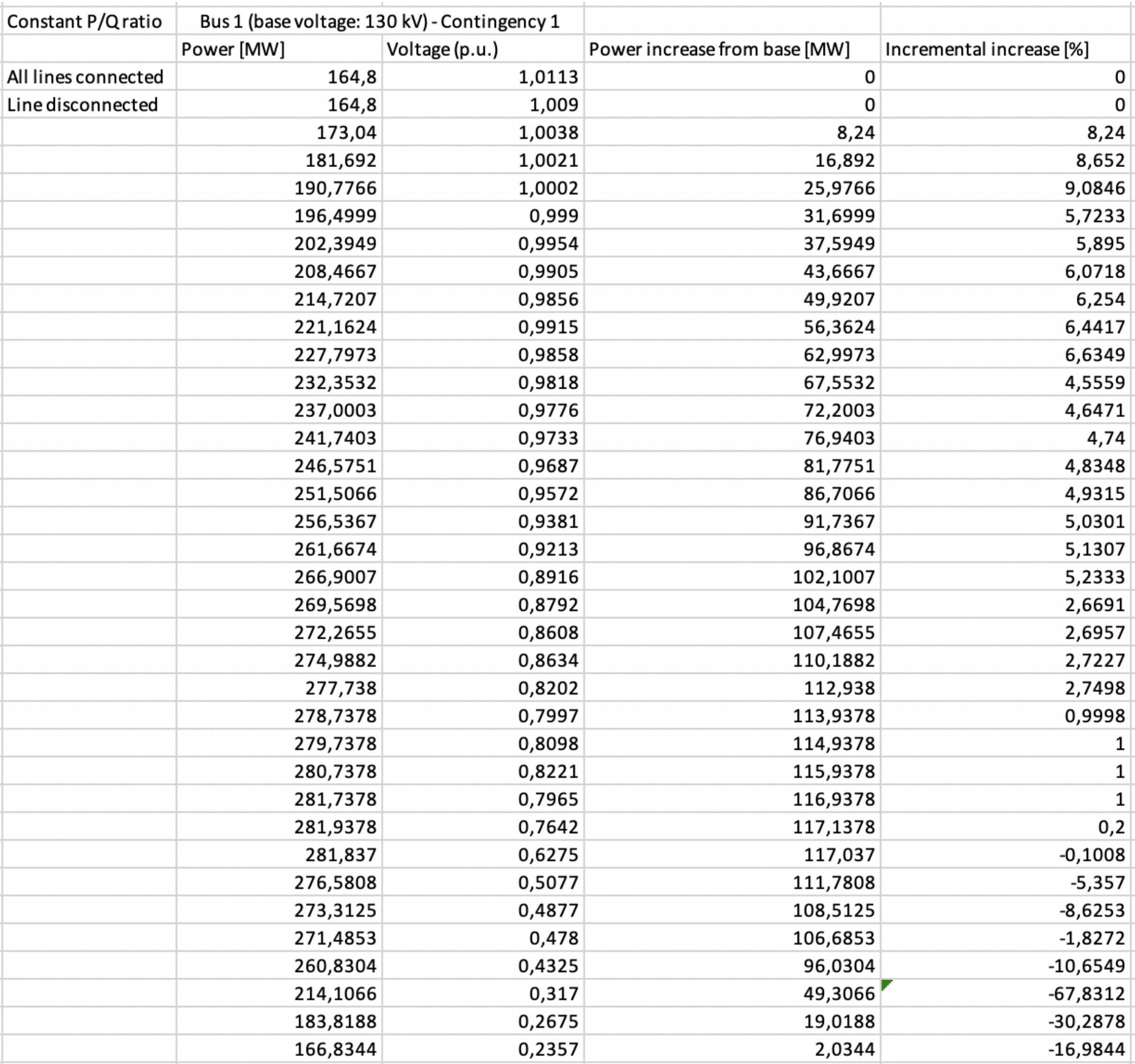
Appendix A. Technology Readiness Level (TRL) Description

Table A.1: A description of the different TRL-levels, going from basic principles to implementation and application. Descriptions retrieved from Statnett [26].



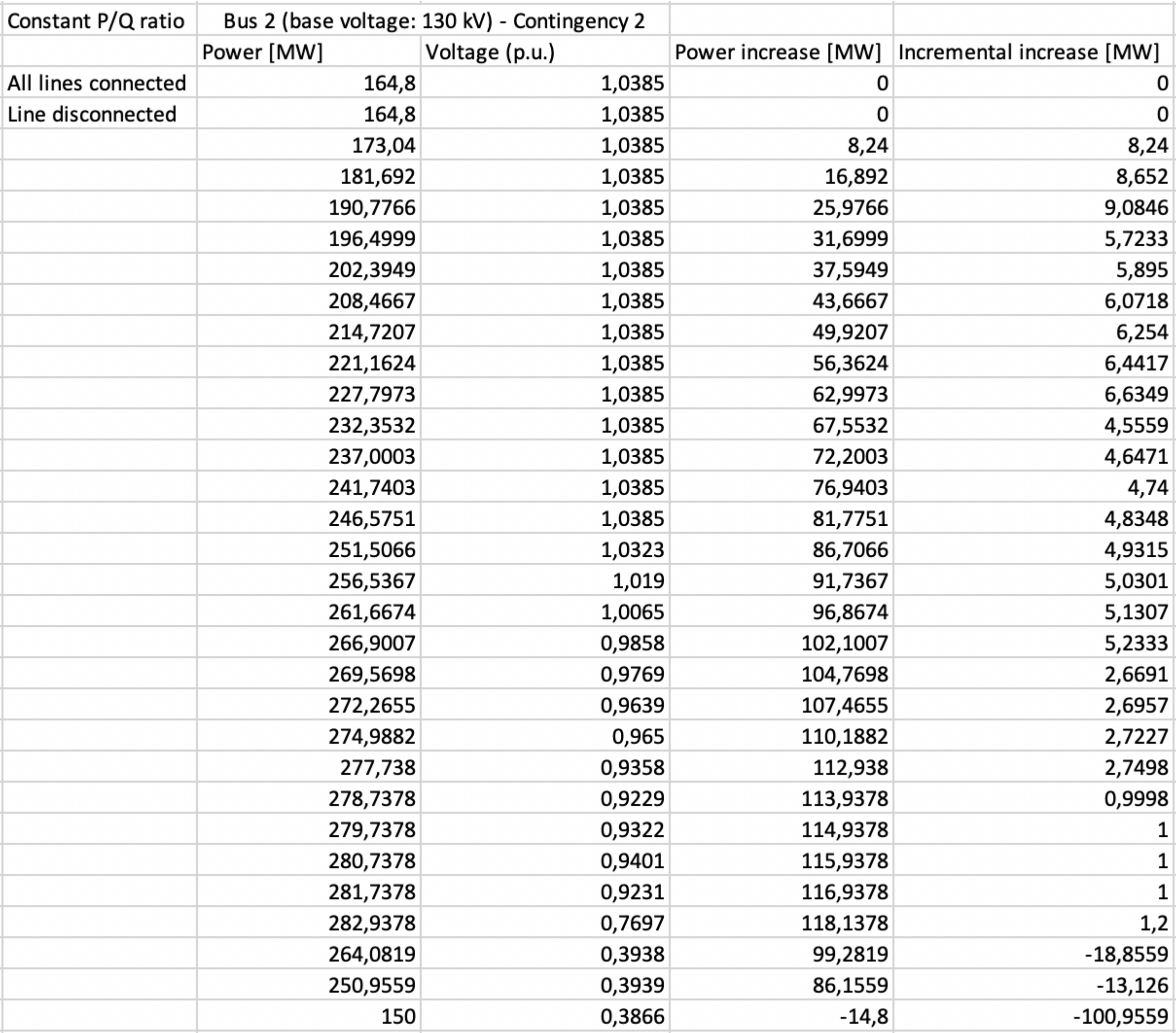
TRL-Level	Level qualifications	
1	Literature studies are executed to confirm the basic principles of the technology. A possible case based on the identified principles is suggested.	Building competence
2	Practical application of the method, the need for further research is established, and case limitations are established. Initial analytical studies are conducted to support the concept to generate new knowledge/data	Research
3	Initial work on the project has commenced, including analytical studies to prove that the concept is viable and new knowledge/data is serviceable.	
4	Fundamental parts of the new method are developed and adjusted to the current needs. The method for the development of knowledge/data is refined to verify its applicability.	Development
5	All parts of the method are now integrated to confirm that they link up. The concept is tested in realistic cases.	
6	The practical feasibility of the new concept is evaluated with realistic cases. The method for the development of knowledge/data is tested on a limited area by examining the whole process, including the analysis of data.	Piloting
7	The new concept is demonstrated in a working environment, integrated with former, operative solutions. New knowledge/data is produced, analysed, and applied in future operative processes.	
8	The concept is used and evaluated in real, operative situations.	Implementation
9	The concept is applied in its final form over an extended period of time.	

Appendix B. PSS/E Data Output in Excel



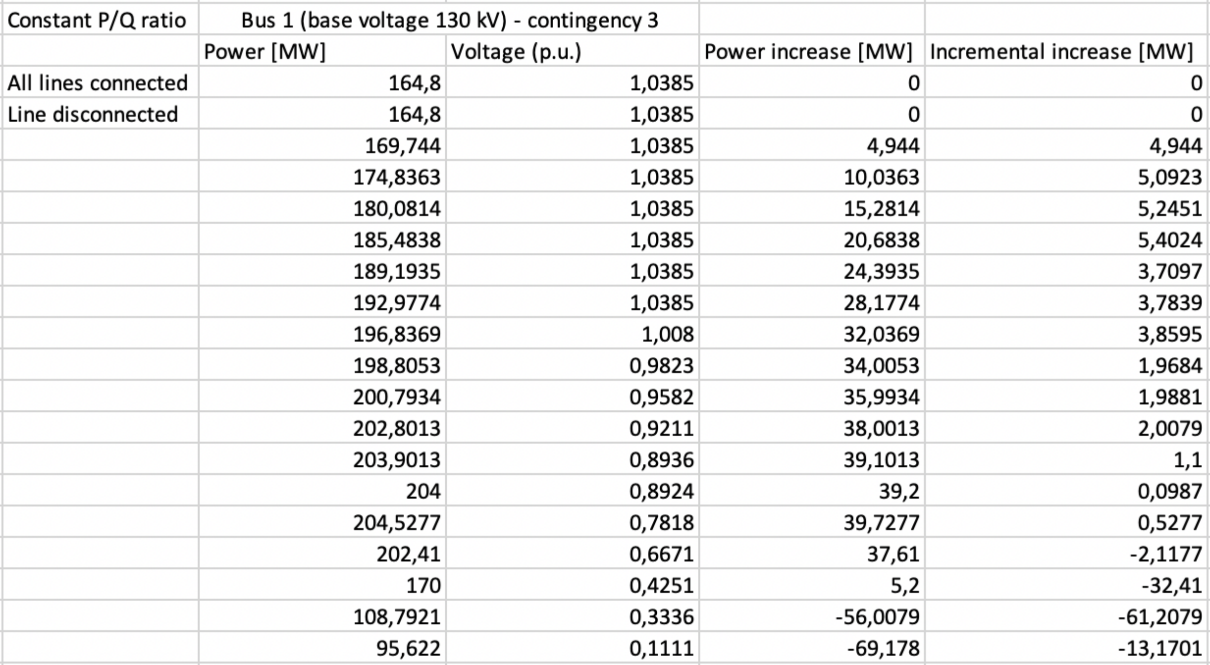
Constant P/Q ratio	Bus 1 (base voltage: 130 kV) - Contingency 1			
	Power [MW]	Voltage (p.u.)	Power increase from base [MW]	Incremental increase [%]
All lines connected	164,8	1,0113	0	0
Line disconnected	164,8	1,009	0	0
	173,04	1,0038	8,24	8,24
	181,692	1,0021	16,892	8,652
	190,7766	1,0002	25,9766	9,0846
	196,4999	0,999	31,6999	5,7233
	202,3949	0,9954	37,5949	5,895
	208,4667	0,9905	43,6667	6,0718
	214,7207	0,9856	49,9207	6,254
	221,1624	0,9915	56,3624	6,4417
	227,7973	0,9858	62,9973	6,6349
	232,3532	0,9818	67,5532	4,5559
	237,0003	0,9776	72,2003	4,6471
	241,7403	0,9733	76,9403	4,74
	246,5751	0,9687	81,7751	4,8348
	251,5066	0,9572	86,7066	4,9315
	256,5367	0,9381	91,7367	5,0301
	261,6674	0,9213	96,8674	5,1307
	266,9007	0,8916	102,1007	5,2333
	269,5698	0,8792	104,7698	2,6691
	272,2655	0,8608	107,4655	2,6957
	274,9882	0,8634	110,1882	2,7227
	277,738	0,8202	112,938	2,7498
	278,7378	0,7997	113,9378	0,9998
	279,7378	0,8098	114,9378	1
	280,7378	0,8221	115,9378	1
	281,7378	0,7965	116,9378	1
	281,9378	0,7642	117,1378	0,2
	281,837	0,6275	117,037	-0,1008
	276,5808	0,5077	111,7808	-5,357
	273,3125	0,4877	108,5125	-8,6253
	271,4853	0,478	106,6853	-1,8272
	260,8304	0,4325	96,0304	-10,6549
	214,1066	0,317	49,3066	-67,8312
	183,8188	0,2675	19,0188	-30,2878
	166,8344	0,2357	2,0344	-16,9844

Figure B.1: The data from PSS/E inserted to Excel to create the PV curve for Contingency 1.



Constant P/Q ratio	Bus 2 (base voltage: 130 kV) - Contingency 2			
	Power [MW]	Voltage (p.u.)	Power increase [MW]	Incremental increase [MW]
All lines connected	164,8	1,0385	0	0
Line disconnected	164,8	1,0385	0	0
	173,04	1,0385	8,24	8,24
	181,692	1,0385	16,892	8,652
	190,7766	1,0385	25,9766	9,0846
	196,4999	1,0385	31,6999	5,7233
	202,3949	1,0385	37,5949	5,895
	208,4667	1,0385	43,6667	6,0718
	214,7207	1,0385	49,9207	6,254
	221,1624	1,0385	56,3624	6,4417
	227,7973	1,0385	62,9973	6,6349
	232,3532	1,0385	67,5532	4,5559
	237,0003	1,0385	72,2003	4,6471
	241,7403	1,0385	76,9403	4,74
	246,5751	1,0385	81,7751	4,8348
	251,5066	1,0323	86,7066	4,9315
	256,5367	1,019	91,7367	5,0301
	261,6674	1,0065	96,8674	5,1307
	266,9007	0,9858	102,1007	5,2333
	269,5698	0,9769	104,7698	2,6691
	272,2655	0,9639	107,4655	2,6957
	274,9882	0,965	110,1882	2,7227
	277,738	0,9358	112,938	2,7498
	278,7378	0,9229	113,9378	0,9998
	279,7378	0,9322	114,9378	1
	280,7378	0,9401	115,9378	1
	281,7378	0,9231	116,9378	1
	282,9378	0,7697	118,1378	1,2
	264,0819	0,3938	99,2819	-18,8559
	250,9559	0,3939	86,1559	-13,126
	150	0,3866	-14,8	-100,9559

Figure B.2: The data from PSS/E inserted to Excel to create the PV curve for Contingency 2.



Constant P/Q ratio	Bus 1 (base voltage 130 kV) - contingency 3			
	Power [MW]	Voltage (p.u.)	Power increase [MW]	Incremental increase [MW]
All lines connected	164,8	1,0385	0	0
Line disconnected	164,8	1,0385	0	0
	169,744	1,0385	4,944	4,944
	174,8363	1,0385	10,0363	5,0923
	180,0814	1,0385	15,2814	5,2451
	185,4838	1,0385	20,6838	5,4024
	189,1935	1,0385	24,3935	3,7097
	192,9774	1,0385	28,1774	3,7839
	196,8369	1,008	32,0369	3,8595
	198,8053	0,9823	34,0053	1,9684
	200,7934	0,9582	35,9934	1,9881
	202,8013	0,9211	38,0013	2,0079
	203,9013	0,8936	39,1013	1,1
	204	0,8924	39,2	0,0987
	204,5277	0,7818	39,7277	0,5277
	202,41	0,6671	37,61	-2,1177
	170	0,4251	5,2	-32,41
	108,7921	0,3336	-56,0079	-61,2079
	95,622	0,1111	-69,178	-13,1701

Figure B.3: The data from PSS/E inserted to Excel to create the PV curve for Contingency 3.

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

Postboks 5003
NO-1432 Ås
Norway