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Situational Awareness in the Power System Control Room of the Future
- a NEWEPS Approach

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Environmental Physics and Renewable Energy

Projects we have completed demonstrate what we know
- future projects decide what we will learn

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Preface

Five years have passed since I first entered the halls of the Norwegian University of Life Sciences (NMBU). The period has been filled with unique experiences from start to finish, shared with fantastic fellow students. NMBU has contributed to my personal growth, both academically and socially. I am forever grateful for the memories we have created here!

This master's thesis is my final project at NMBU before I embark on new adventures. I would like to thank my supervisor Sonja Berlijn for the continuous support and valuable feedback during the writing process. Furthermore, the master's thesis has been enriched through the investment of time and competence from several employees at Statnett- for which I am deeply grateful.

The school environment has been characterised by a willingness to share competence and experiences across grade levels and subject areas. This wonderful quality has also accompanied the emergence of this master's thesis. I am especially grateful to my fellow students and project partners Tobias Korten, Krishna Solberg, and Andreas Svanes for our fantastic journey. The collaboration and unity have made the experience far more memorable.

Ås, June, 2021

Ellen Bera Mathiesen

Abstract

Future requirements and challenges related to grid operation cause structural and operational changes in the Nordic synchronous area. Control room personnel are increasingly dependent on mature monitoring, control, and protection technology. The Nordic Early Warning Early Prevention System (NEWEPS) project aims to develop techniques within these fields. This study is a part of Work Package 2 (WP2) within NEWEPS, which is about the visualisation of power system states.

This master's thesis explores future data needs and visualisation techniques to enhance real-time control room operation. State-of-the-art observability at Statnett is mapped through interviews. Key indicators of evolving events in the network are highlighted through literature scoping reviews. Synchrophasor data are shown to reflect the system state related to grid stress, dynamics, and proximity to instability. Furthermore, it eases the detection of oscillations, islanding, and instability. Associated data needs such as angular differences, damping, and voltage sensitivity are also surveyed and justified.

Findings from the literature scoping review suggest that the best visualisation of data is through dynamic graphs and maps. From the scoping review, the Real Time Dynamics Monitoring System (RTDMS) is highlighted as a visualisation tool currently under development. RTDMS enables wide-area monitoring of conditions such as islanding events, oscillations, voltage stability, and grid stress. Findings from the literature scoping review indicate a need for field asset monitoring within the control room. Implementation is found possible through augmented virtuality and digital twins.

Voltage sensitivity and reliability margins are highlighted as indicators of voltage stability in the reviews. Their applicability is evaluated through a case study. Load and transmission changes were simulated in "Sørnettet" in Power System Simulator for Engineering (PSSE). Associated PV curves were assessed for a given bus. Due to the outage of a transmission line, the reliability margin narrowed from the critical point at 320 MW to 250 MW. There was also an increase in sensitivity from -0.066 $\frac{kV}{MW}$ to -0.49 $\frac{kV}{MW}$. These findings indicate that the proposed metrics are useful to assess the vulnerability of the system towards voltage instability.

Sammendrag

Fremtidige krav og utfordringer knyttet til nettdrift fremmer strukturelle og operasjonelle endringer i det nordiske synkronområdet. Kontrollrompersonell er i økende grad avhengig av velutviklet overvåkings-, kontroll-, og beskyttelsesteknologi. Prosjektet *Nordic Early Warning Early Prevention System* (NEWEPS) har som mål å utvikle teknikker innen disse feltene. Denne masteroppgaven er en del av arbeidspakke 2 (WP2) i NEWEPS, som handler om visualisering av kraftsystemtilstander.

Masteroppgaven utforsker fremtidige databehov og visualiseringsteknikker for å forbedre sanntidsdrift i kontrollrom. Det nåværende informasjonsbildet hos Statnett er kartlagt gjennom intervjuer. Fremtidige nøkkelindikatorer for hendelser i nettverket har blitt fremhevet gjennom en scoping review. Synkronfasedata vises å reflektere systemtilstanden relatert til nettstress, dynamikk og sårbarhet for ustabilitet. Videre tilrettelegger dataene for deteksjon av oscilleringer, øydrift og ustabilitet. Assosierte indikatorer som vinkelforskjeller, demping og spenningssensitivitet er også kartlagt og begrunnet.

Funn fra scoping reviewen tyder på at den beste visualiseringen av data fremmes av dynamiske grafer og kart. Gjennom scoping reviewen fremmes *Real Time Dynamics Monitoring System* (RTDMS) som et visualiseringverktøy som utvikles. RTDMS tilrettelegger monitorering av tilstander som øydrift, oscilleringer, spenningsstabilitet og nettstress. Funn fra scoping reviewen indikerer et behov for feltovervåkning i kontrollrommet. Implementering fastslås mulig gjennom utvidet virtualitet og digitale tvillinger.

Spenningssensitivitet og pålitelighetsmarginer fremmes som indikatorer for spenningsstabilitet i scoping reviewen. Deres anvendbarhet ble evaluert gjennom en case studie. Last- og transmisjonsendringer ble simulert for Sørnettet i *Power System Simulator for Engineering* (PSSE). Tilhørende PV-kurver ble betraktet for en gitt node. Grunnet utfall av en transmisjonslinje, ble pålitelighetsmarginen redusert fra det kritiske punktet ved 320 MW til 250 MW. Det var også en økning i følsomhet fra -0,066 $\frac{kV}{MW}$ til -0,49 $\frac{kV}{MW}$. Disse funnene indikerer at de foreslåtte indikatorene er nyttige for å vurdere systemets sårbarhet for spenningsustabilitet.

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Abbreviations

AGC	Automated Generation Control
AI	Artificial Intelligence
AV	Augmented Virtuality
CP	Cyber-Physical Systems
DSA	Dynamic Security Assessments
DSO	Distribution System Operator
ELECTRA	European Liason Electricity Committed Towards Research Activity
ENTOS-E	European Network of Transmission System Operators
EPG	Electric Power Group
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
EU	European Union
GPS	Global Positioning System
HV	High Voltage
HVDC	High-Voltage Direct Current
ICT	Information and Communications Technology
MV	Medium Voltage
NASPI	North American SynchroPhasor Initiative
NEWEPS	Nordic Early Warning Early Prevention System
NMBU	Norwegian University of Life Sciences
P2X	Power-2-X
PMU	Phasor Measurement Unit
PSSE	Power System Simulator for Engineering
RES	Renewable Energy Sources
RGB	Red Green Blue

ROCOF	Rate Of Change Of Frequency
ROCOOP	Rate of Change of Output Power
RTDMS	Real Time Dynamics Monitoring System
SA	Situational Awareness
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SSA	Static Security Assessments
TRL	Technology Readiness Level
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
WAM	Wide Area Monitoring
WP2	Work Package 2

1. Introduction

1.1 Background and Motivation

Emission-heavy energy production and consumption accounts for a large share of emitted greenhouse gases in the European Union (EU) [1]. Future implementation of Renewable Energy Sources (RES) is essential to meet up with climate objectives. The energy carrier of the future is electricity [2]. Consequently, the power grid must facilitate an electrical power demand increase in Europe four to six times greater than present demand [3]. Future operation will be characterised by new generation and consumption patterns, sector coupling, and technology development. The power grid requires updating and well-thought-out solutions, because of these developments.

Present control room personnel depend on sufficient tools to manage the increasing complexity of the grid. Such tools can be based on rapid and high-resolution data and visualisation techniques. The project Nordic Early Warning Early Prevention System (NEWEPS) addresses system monitoring and control, through nine work packages. Work package 2 (WP2) targets methods for visualisation of the power system state in the control centres. Several doctor fellows are planned to be involved in the project. With increased insight into the breadth and depth of the network, one can promote situational awareness. Hence, operators will be more capable of making well-informed decisions promptly [4]. Thus, this master's thesis aims to contribute to insight and understanding within the subject of real-time control room situational awareness.

1.2 Scope and Limitations

This master's thesis consists of interviews, literature scoping reviews, and a case study. The Norwegian University of Life Sciences (NMBU) operates with a writing period of four months for master students. For efficient use of time, scoping literature reviews were conducted in January to early April 2021. The preliminary part revolved around immersion in the project and subject matter.

To provide a relevant and precise perception of the substance, interviews were conducted with one expert within the field of real-time control room operation. In total, two interviews were conducted between January and March. The amount of time spent conducting interviews was weighed against the purpose of the interviews. The interviews were to depict an overview of state-of-the-art observability at Statnett. Additionally, they intended to emphasise the gap between current and future solutions. Hence, numerous interviewees were not considered necessary. Rather, emphasis was placed on the experience and competence of the selected interviewee.

The latter part of April was spent exploring a case study. This was prioritised as it may add weight to the presented material and motivation for further research. However, a large selection of monitoring parameters has proven useful in this master's thesis. Thus, it would be too extensive to include all the parameters in the case based on the given time frame. NEWEPS focuses on indicators of voltage and frequency stability and damping of electromechanical oscillations [5]. Consequently, the author chose to focus on voltage stability monitoring. Additionally, it was redeemed necessary to get acquainted with the software tool Power System Simulator for Engineering (PSSE).

1.3 Research Questions

The main purpose of this master's thesis is to present possible solutions that can increase situational awareness in the power system control rooms of the future. The solutions should extend beyond current procedures at Statnett. Statnett is the Norwegian Transmission System Operator (TSO). Two research questions were formulated, these are presented below:

- *What data is necessary to improve the situational awareness in the power system for the control rooms of the future?*
- *How should the data be visualised?*

Sub-questions were formulated to sculpt relevant solutions to the tasks of concern. These are presented below:

1. Sub-questions to address the first research question:
    - What data is already available?
    - What data is necessary for different types of operational situations?
2. Sub-questions to address the second research question:
    - How is the data best visualised?
    - What visualisation solutions are currently being developed?

2. Challenges in the Nordic Synchronous Network

2.1 Grid Structure in the Nordics

The Nordic synchronous area consists of Norway, Sweden, Finland, and Denmark [6]. This area operates with a nominal frequency of 50 Hz. Such a frequency can be obtained during perfectly balanced operation. Balanced operation implies a correspondence between power import and production relative to export, consumption, and losses as stated in equation (2.1). Excessive access to power will increase the frequency, whilst insufficient access decreases it.

$$Production + Import = Consumption + Export + Losses. \tag{2.1}$$

Imbalances in the grid can be classified as structural or stochastic. To facilitate balance during operational planning, production and consumption are predicted on an hourly basis. Due to the limited time resolution, consumption and production may vary within the hour. Such variations may lead to structural imbalances in frequency. Stochastic imbalances are on the other hand related to technical anomalies. This could be caused by cuts in production or component failures. To maintain balance and good frequency quality, the frequency should be kept between 49,9 Hz and 50,1 Hz [8].

Interconnectors are cables that enable power flow between different networks. Excess-generated power can thus be shared or traded. Such connections link Norway to Sweden, Denmark, Finland, and the Netherlands. These countries are also linked with other parts of Europe [9]. Therefore, the production and consumption in Europe can indirectly affect the power situation in Norway. Figure 2.1 illustrates power flow and pricing regions in the Nordic area. Prices are given in € per MWh, and power flow in MW [7].

Nordic electricity generation is diverse. Hydropower is the main source of generation in Norway. Due to its extensive production, Norway exports more power than it imports

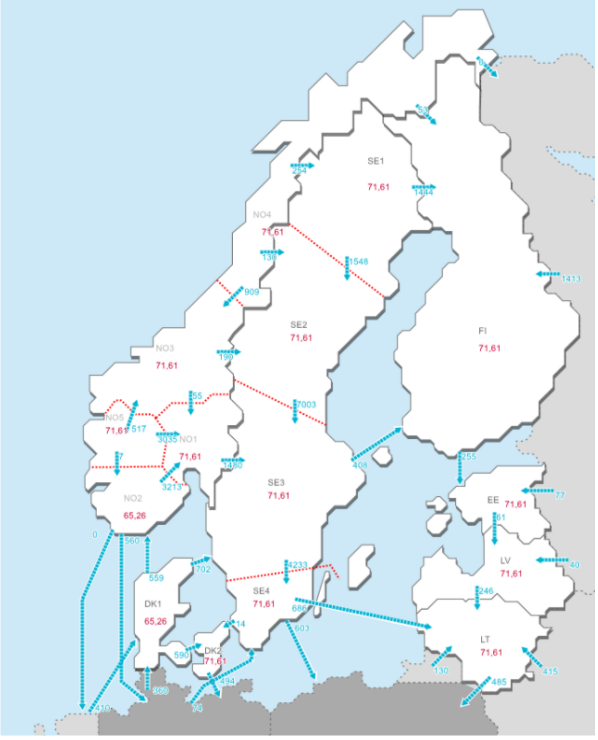


Figure 2.1: Nordic power flow (MW) presented in blue and pricing (€ per MWh) in red [7].

most of the time. Sweden has a production mix dominated by hydro and nuclear power. Thermal electricity production is common in both Denmark and Finland. Denmark additionally has wind production, whereas Finland profits from nuclear power [9].

2.2 The European Green Deal

The European Green Deal is an action plan developed by the European Commission. It was created with the intent to make the EU climate-neutral by 2050. Climate-neutrality implies net-zero greenhouse gas emissions. By 2030 this reduction is targeted to be at 50-55 % [1]. Clean, affordable, and safe energy is at centre during this transformation, as seen in Figure 2.2. To achieve these objectives, Europe must facilitate massive decarbonisation. The electrical grid plays a crucial role in assisting this process- it is even said to be the backbone of the transformation [2].

In 2018 the European Commission stated that more than 75 % of the EU's greenhouse gas emissions originated from production and use of energy [1]. Decarbonising Europe implicates transitioning from emission-heavy generation to renewable energy production. Consequently, the share of electricity in the final energy demand will increase. It will lead to an electrical power demand increase in Europe four to six times greater than present demand. Electrification is one of the main routes for decarbonisation. Therefore, the electricity generation must expand from the present approximate value of 20 000 TWh

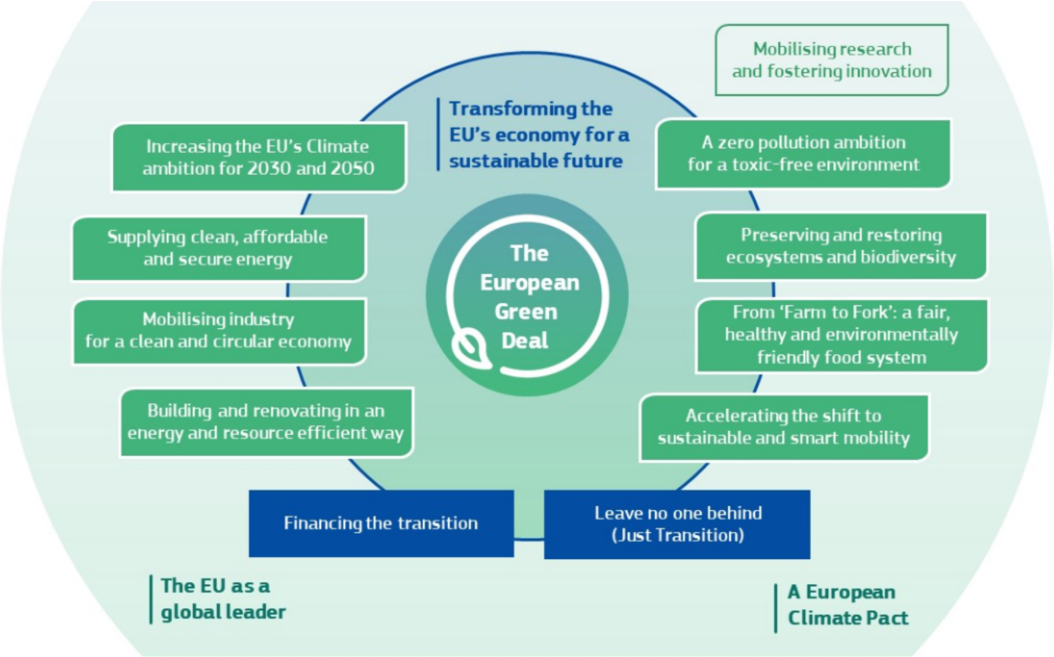


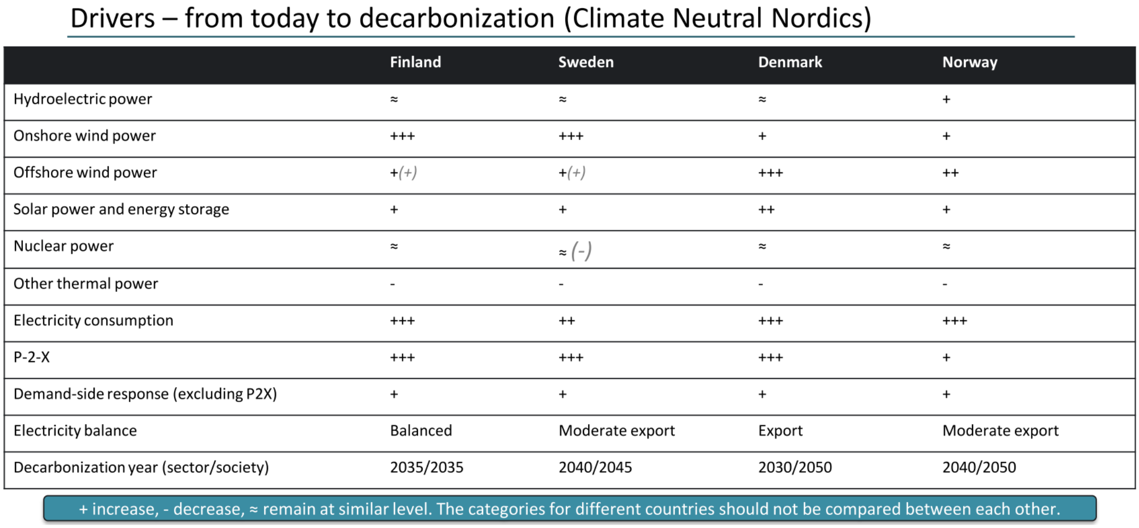
Figure 2.2: Overview of objectives stated in The European Green Deal [10].

to 85 000 - 115 000 TWh by mid-century. Approximately 85 - 90 % of the electricity will be produced through renewables or zero-carbon electricity generation [3]. Consequently, enhanced integration of renewable energy sources into the grid is crucial.

Increased usage of variable energy resources such as wind and solar leads to more fluctuating energy production. As the balance between production and consumption is essential for a well-functioning power grid, such fluctuations must be accounted for in short, medium, and long term. To maintain balance in the European grid, improved cross-border and regional cooperation is necessary. Accessibility to clean energy will then be promoted.

Nordic electricity generation and trade is an example of promising cross-border cooperation. The Nordic area has a considerable amount of clean energy sources. Some of these are presently being utilised, but additional production is achievable [9]. The Nordic Grid Development Perspective introduces probable drivers towards decarbonization in the Nordics by 2050 in Table 2.1. An expansion in wind power and Power-to-X (P2X) is particularly highlighted. According to the Swiss Competence Centre for Energy Research, P2X: "*refers to technologies that use (surplus) electricity, ideally from fluctuating renewable energy sources, to synthesise (gaseous) chemical products, like hydrogen or hydrocarbons*" [12]. By exporting clean energy, one may discharge more emission-heavy generation. Controllable hydropower is also available in the Nordics. This facilitates a certain amount of balancing services to the increasing variable energy production [9].

Table 2.1: Probable drivers to decarbonization in the Nordics by 2050 presented by the Nordic Grid Development Perspective [11].



Drivers – from today to decarbonization (Climate Neutral Nordics)

	Finland	Sweden	Denmark	Norway
Hydroelectric power	≈	≈	≈	+
Onshore wind power	+++	+++	+	+
Offshore wind power	+(+)	+(+)	+++	++
Solar power and energy storage	+	+	++	+
Nuclear power	≈	≈ (-)	≈	≈
Other thermal power	-	-	-	-
Electricity consumption	+++	++	+++	+++
P-2-X	+++	+++	+++	+
Demand-side response (excluding P2X)	+	+	+	+
Electricity balance	Balanced	Moderate export	Export	Moderate export
Decarbonization year (sector/society)	2035/2035	2040/2045	2030/2050	2040/2050

+ increase, - decrease, ≈ remain at similar level. The categories for different countries should not be compared between each other.

2.3 Ten Year Network Development Plan

The Ten Year Network Development Plan (TYNDP) is established by the European Network of Transmission System Operators for Electricity (ENTSO-E). Recommendations for grid development are presented in a time perspective of 10 to 20 years. The latest release was published in 2020 [13]. It addresses grid development considering the security of supply, affordable energy prices and sustainable development. EU's climate objectives are also considered. Here, ENTSO-E emphasises the transmission networks role in the rapid transition towards renewable energy resources.

ENTSO-E states that successful decarbonisation and implementation of variable energy resources is dependent on two factors. Firstly, the cost of transforming the power sector must be kept minimal. Enhanced market integration and competitive power prices will be enabling components. The second factor is continuous secure access to electricity for all Europeans. This requires the electricity system planning to be coordinated and pan-European [2]. The Ten Year Network Development Plan aims to be such an approach.

Addressing system needs is the first step to realise The Green Deal. The future power system is predicted to be more integrated and dynamic between all the value chains. Increased integration implies more interaction between energy sources such as electricity, heat, biofuels, natural gas, and hydrogen [14]. Electricity is anticipated to account for up to 65 % of the energy transfer [2]. Technological solutions and modern infrastructure are therefore essential to accommodate future requirements.

Fundamentally, the power system operation of the future will mainly be affected by the following factors [2]:

1. New generation patterns
2. New consumption patterns
3. Decentralisation of energy resources
4. Sector coupling
5. Technology development.

2.4 Nordic Challenges Report

There are four Nordic TSOs, namely Statnett, Fingrid, Energinet and Svenska kraftnät. The TSOs have collectively developed the Nordic Challenges Report. The report aims to affirm challenges affecting the Nordic power system leading up to 2025. Fundamental changes in climate policies affect the operation of the Nordic power system. Further deployment of renewable energy sources and technological solutions is expected. Additionally, a collective European framework for markets, operation and planning will evolve [15]. Hence, structural changes are required for the forecasting, operation and planning of the Nordic power system.

The Nordic Challenges Report presents three principal concerns in the Nordic grid leading up to 2025. Firstly, meeting the demand for flexibility. Figure 2.3 illustrates the increasing need for flexibility. The Nordic TSOs define flexibility as "*the controllable part of production and consumption that can be used to change input or output for balancing purposes*" [15]. The Nordic Challenges Report states that irregular renewable production is the main cause for the increased flexibility demand.

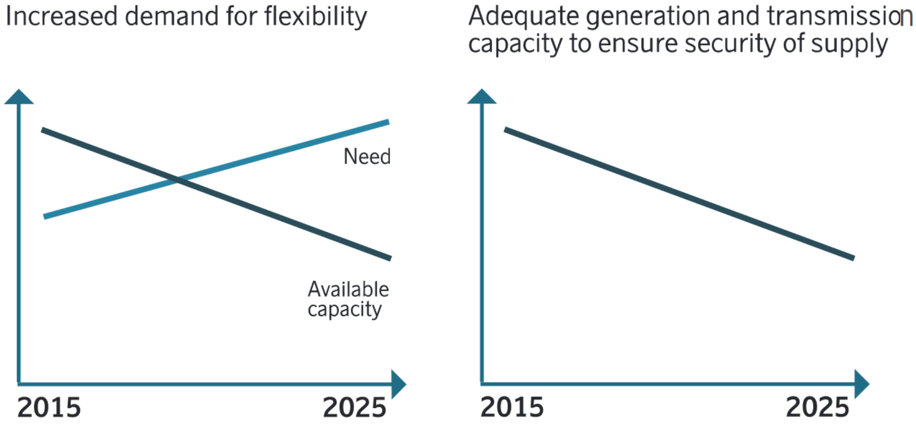


Figure 2.3: Expected development of flexibility demand and generation and transmission capacity towards 2025 [8]. Courtesy of Sonja Berlijn.

The second challenge is ensuring adequate transmission and generation capacity to guarantee the security of supply and to meet the demand of the market. Figure 2.3 depicts a decrease in such capacity towards 2025. Adequate generation is challenged by pricing and methodologies. Pricing may constrain regulatory actions from power plants when deviating from profitable prices. Simultaneously, current methodologies do not consider all uncertainties in the power system (e.g. component failure). Regarding transmission capacity, one aspires to preserve resources for balance and security of supply [15].

The third challenge is maintaining sufficient inertia and good frequency quality in the system to ensure operational security. Inertia is associated with the rate of change of frequency. Inadequate inertia may lead to prompt frequency drops. Rapid and extensive changes are undesirable as they can trigger protection mechanisms before the implementation of preventative measures. An example is load shedding relays which may disconnect load due to the rapid change of frequency. The available inertia to support system stability is decreasing, as illustrated in Figure 2.4. Implementation of renewable energy sources causes a reduction of inertia. Reduced inertia is also caused by high import through high-voltage direct current (HVDC) connections and the phasing out of nuclear units [15].

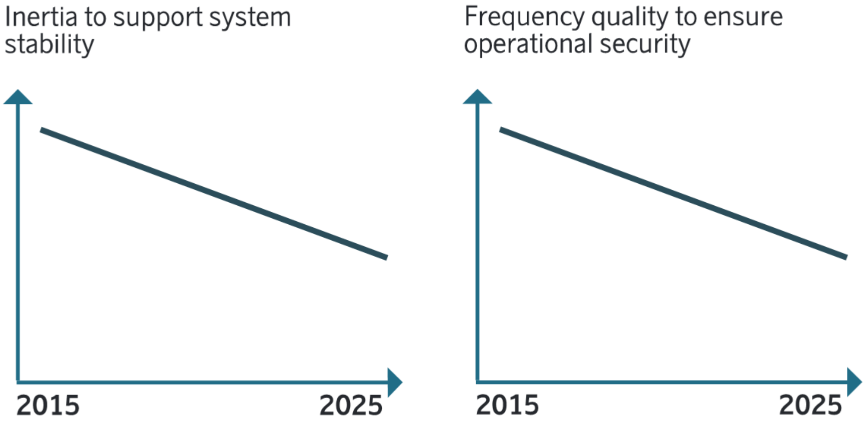


Figure 2.4: Expected development of inertia access and frequency quality in the electrical grid towards 2025 [8]. Courtesy of Sonja Berlijn.

Frequency quality indicates the level of system security in the grid. Figure 2.4 illustrates the declining frequency quality towards 2025. Deviations outside 49,9 - 50,1 Hz challenge system security to varying extent [16]. System security represents the grids ability to meet the power demand. Sufficient frequency and balancing reserves are crucial to secure real-time balance. Current market designs operate with hourly resolutions for balance. Nevertheless, there is an increasing amount of intra-hour imbalances. Generation changes cause this tendency and lead to greater forecast failures [15].

Currently, the share of wind power in the Nordic area is increasing. However, the fluctuating characteristic of wind presents some challenges. The generation of energy may change rapidly and therefore increases the need for flexibility in the grid. Simultaneously, a high share of wind power limits the amount of inertia in the system. The Nordic area is also reducing the number of active thermal power plants. Decommissioning reduces the flexibility of the system. Finland is implementing new nuclear capacity, while Sweden somewhat reduces it. By reducing the number of nuclear power plants, inertia in the system decreases. Regarding interconnectors, their capacity will increase by more than 50 % by 2025 [15]. This facilitates additional cross-border trade and balancing services.

2.5 Research, Development and Innovation Roadmap 2020 - 2030

ENTSO-E's Research, Development, and Innovation Roadmap tailor solutions for emerging challenges in the electrical grid. The focal point is the improvement of market design and system operation in the transmission system by 2030. The roadmap consists of three priority areas, presented in Figure 2.5. The different priority clusters consist of several flagship projects within the areas of research, development, and innovation.

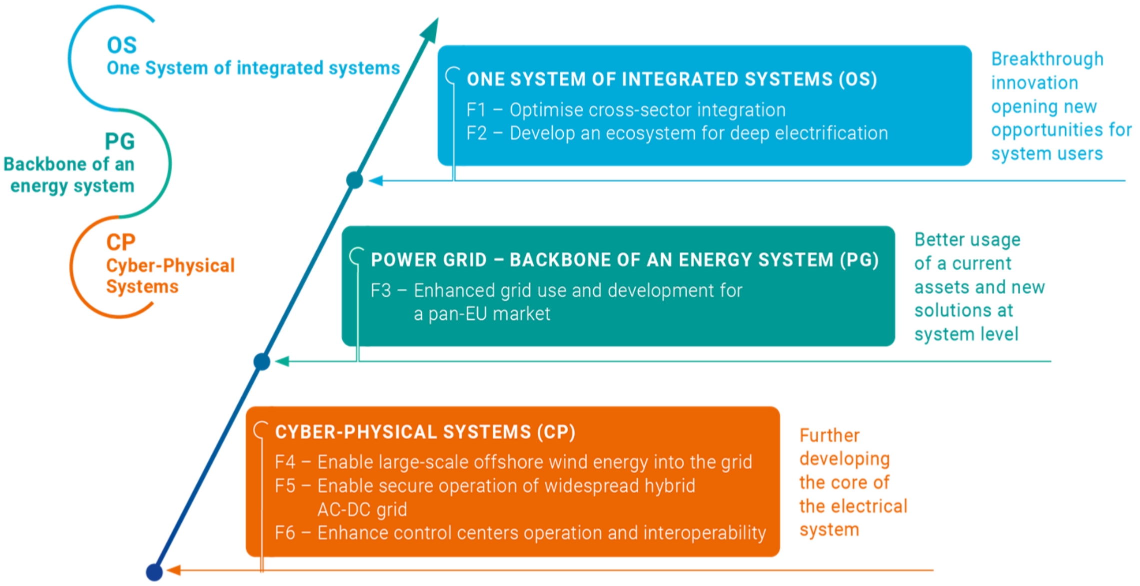


Figure 2.5: ENTSO-E's Reasearch, development and innovation roadmap for 2020-2030. Three priority clusters are presented with associated flagships [17].

The cyber-physical system cluster (CP) addresses the considerable integration of power electronics in the power system. It also focuses on additional digitalisation and enhanced connectivity in the grid. Secure interoperability of grid components is essential for the progress towards 2025. This includes both hardware and software. As the need for real-time operation increases, new standards and interoperable technologies are fundamental.

Therefore, more computer-human interaction is needed. Flagship 6's goal is to enhance control centre operation and interoperability. To address the increasing complexity and interconnection of the power grid, the control centres need enhancements. Further research must be conducted on the interoperability of control centres [17]. Figure 2.6 presents guidelines and tools to manage the complexity of Flagship 6.

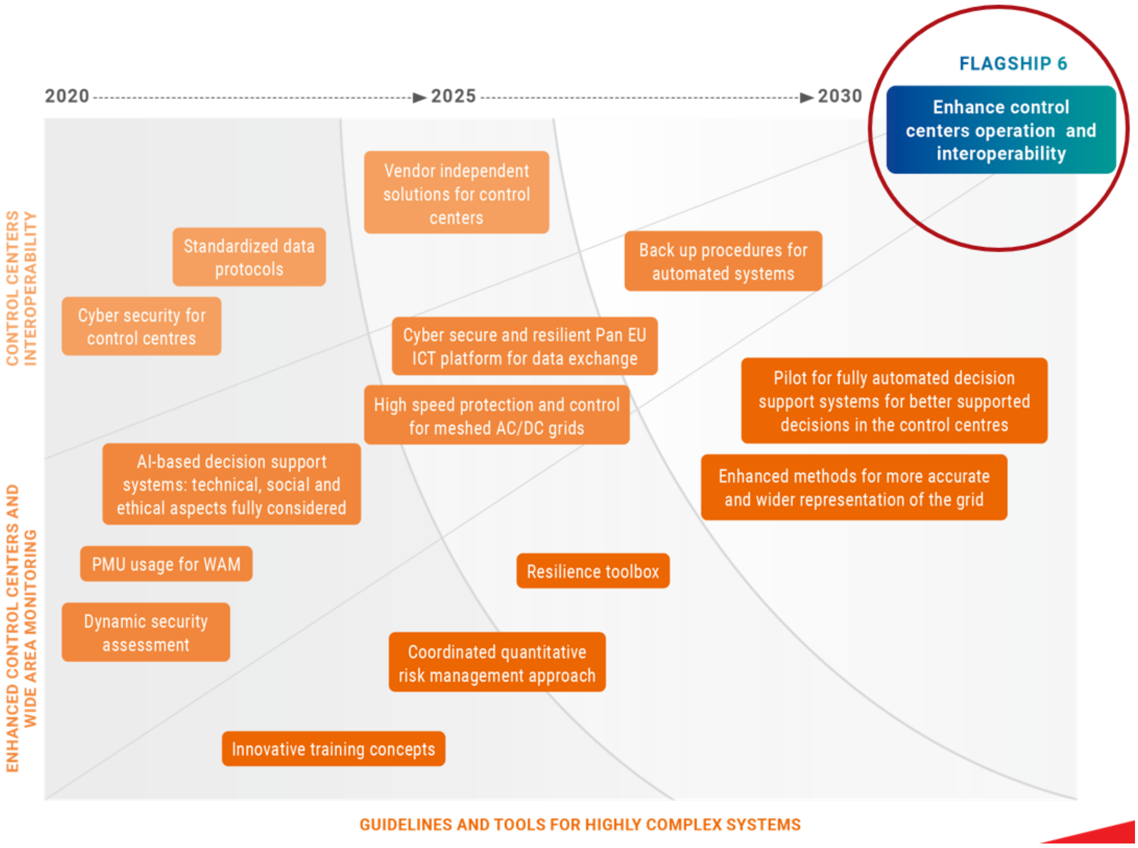


Figure 2.6: Proposed guidelines and tools to enhance control centres operation and interoperability towards 2030. The presented elements supplement Flagship 6 [17].

Future control centre operation will be characterised by faster dynamics and include data from Phasor Measurement Units (PMU). These will be used for Wide Area Monitoring (WAM) and serve as an enhancement of control centres. Future control centres will benefit and rely on enhanced Information and Communications Technology (ICT) infrastructure. This will improve system monitoring and control capabilities. Decision support will be based on Artificial Intelligence (AI) and automated systems. The information load in the control centres is increasing and becoming more complex. There will be a need for innovative training approaches for control room operators. Human intervention may be required, and operators must know how to implement corrective actions. Wider representations of the depth and breadth of the grid may lead to improved situational awareness. This enhances well-supported decisions in the control centres, especially in critical situations [17].

2.6 Nordic Early Warning Early Prevention System

Nordic Early Warning Early Prevention System is a Nordic project aiming to secure reliable system operation, which is currently affected by several development trends. These trends include energy transitioning, market integration and digitalisation. NEWEPS will improve Nordic system operation to facilitate the ongoing changes. System operation methods used today have to a large extent been developed during the 1970-80's. Modern digitalisation facilitates big data management and offers an ocean of possibilities. This involves usage of PMUs, data storage, algorithms, and user interfaces [4].

Techniques for power system monitoring and control is the focal point of NEWEPS. Mature monitoring, control and protection applications shall be promoted for the Nordic TSOs. Real-time measurements shall be utilised for system security and stability. The future operation of power systems demands increased awareness and stability in the system. Handling a substantial increase in data, number of events, and less time to act requires decision support for operators, as well as automation. To benefit from information within the data, efficient collection, processing, and accessibility is crucial. Real-time operation demands real-time information flow and hence improved ICT structure.

NEWEPS consists of several work packages, which target different parts of the project. Figure 2.7 displays an overview of the various components of the project.

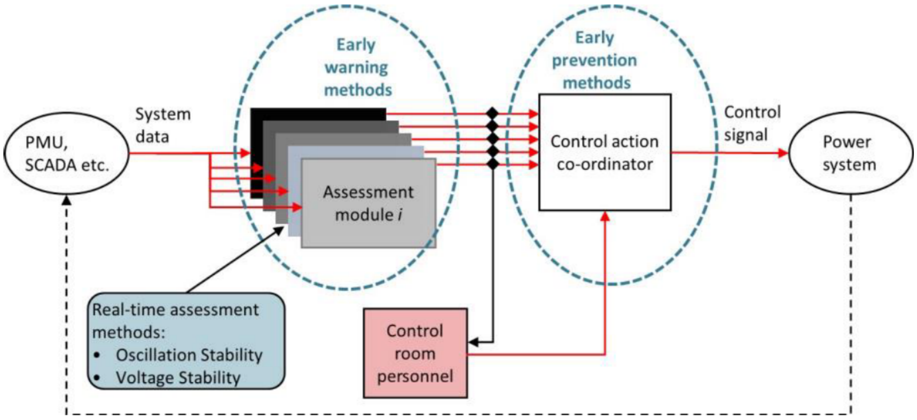


Figure 2.7: Conceptual overview of the Nordic Early Warning Early Prevention System (NEWEPS) [4]. Courtesy of Sonja Berlijn.

WP2 targets methods for visualisation of the power system state in the control centres. Proper corrective measures of system operation are supported by increased system awareness. Measures that can improve situational awareness include:

- Illustrating overall system state

- Illustrating system details
- Predicting probable development in near future
- Early warning signals
- Proposed control actions and their impact on stability margins.

All of which must be displayed clearly and visually. Concepts for visualisation could be retrieved from existing visualisation methods, and research on efficient visualisation techniques [4]. This master's thesis is based on data needs and visualisation techniques related to the grid state. Thus, the findings will be closely linked to WP2.

3. Methodology

3.1 Qualitative Methodology

The starting point of this master's thesis is founded on interviews with an expert within the field of real-time control room operation at Statnett. Additionally, a literature scoping review was conducted in two parts to gain overview knowledge within:

a) Future control room data needs within the transmission system

b) Promising visualisation techniques for real-time operation.

Knowledge obtained from the interviews and literature scoping reviews were further implemented in a brief case study. The case study aimed to shed light on how selected parameters can provide insight into unfolding events in the network.

3.2 Interview Preparations

Reflection of future solutions requires mapping of present operation. Interviews provide a quick and effective situational understanding that can immerse the interviewer into the topic. Semi-constructed respondent interviews were conducted to identify status-quo, relevant needs and perspectives of control room personnel at Statnett. The respondent is an expert within the field of real-time control room operation, with many years of experience from the regional centre in northern Norway.

The interviews took place in two rounds over Microsoft Teams. Notes taken during the interviews were transcribed into a document by the interviewer. Note that the answers are reproduced by the author and are not direct citations from the interviewee. The interviewee has received the minutes for review and has not submitted any proposals for changes. The interviews should provide an overview, and not necessarily detail orientation, of control room operation at Statnett.

At the end of January 2021, the first interview of about an hour and a half was conducted. The interview aimed to map the present scope of information and prevalence of synchrophasor data in the control room. In addition, the interviewee's thoughts on future control room design were examined. The specific interview guide is attached in Appendix D.1. Adjusting queries were asked along the way to highlight relevant points.

The second interview was conducted in early March 2021, after further immersion in literature. This interview aimed to validate findings from the literature scoping review and clarify the gap between current and future operation. Thus, it was desirable to examine how selected events were reflected during operation. The structural division of control room operation within Statnett was also further examined. The specific interview guide is attached in Appendix D.2.

Transcripts from both interviews are attached in Appendix E. Main excerpts from the interviews are presented in Section 5.1. The excerpts have been prioritised on whether they provide an overview regarding themes such as information access, event detection, future development and visualisation.

3.3 Literature Scoping Review Preparations

Due to the study of two research questions, it was found appropriate to perform two discrete literature scoping reviews. Literature was explored in various search databases, where the most frequently used were IEEE, NASPI and ResearchGate. Mainly, the articles were to present solutions that could be linked to the transmission network and real-time operation. In addition, the search has been used to define background concepts and terminology presented in Chapter 4. The literature scoping reviews were carried out in the period January 2021 - April 2021.

The first scoping review aimed to emphasise key data needs within the transmission network that are frequently highlighted in the literature. Thus, the results do not necessarily describe the total data need, but rather trends that appear relevant as of today. Findings from the first scoping literature review form the basis for the results addressed in Chapter 6. The second scoping review highlights possible visualisation solutions for various network data. To assess their level of development, each technology is assigned a Technology Readiness Level (TRL). Findings from the second part of the scoping review are presented in Chapter 7.

The two literature scoping review topics were control room information needs and general visualisation methods. Search strings were combined in several ways to highlight relevant articles. The most frequent search strings are presented below for both search processes. Summaries and conclusions were reviewed to assess the relevance of the articles. Authors of promising texts were examined further to uncover several potentially useful articles.

1. The primary search strings aimed at uncovering relevant information for the first research question. Due to the widespread use of synchrophasors in the United States, literature from this area was examined in particular. The following search strings were used:

   (“Phasor Measurement Units” **OR** “PMU” **OR** “synchrophasor”)

   AND

   (“control room” **OR** “operators” **OR** “situational awareness” **OR** “real-time”)

2. The secondary search strings aimed to uncover relevant information for the second research question. Due to massive advances in the field of visualisation, mainly literature published after 2009 was reviewed. The following search strings were used:

   (“visualisation” **OR** “simulation”)

   AND

   (“techniques” **OR** “methods” **OR** “software”)

To connect visualisation techniques to real-time data, some of the search strings in the first point were combined with the second point as well. The relevance of publications was evaluated through their suitability for real-time operation.

3.3.1 Technology Readiness Level

TRL maps the maturity of a given technology. As definitions and qualifications for TRL may differ between contributors, this thesis will be based on Statnett’s scale. Figure 3.1 from Statnett illustrates nine TRLs’. The scale relates low TRL to startup phases. Higher degrees of TRL may indicate that the technology is implemented in existing environments. Qualifications for the various levels are presented in Appendix A.

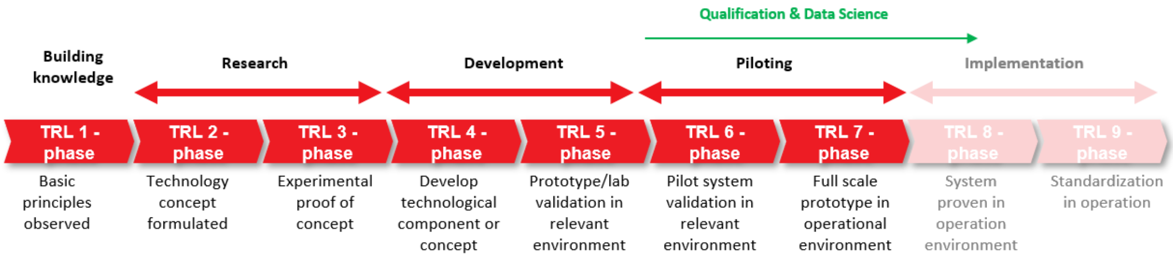


Figure 3.1: Technology Readiness Level (TRL). This TRL scale consists of nine levels [18]. Usage authorised by Sonja Berlijn.

Throughout the text, promising visualisation technologies will be linked to the scale. TRL assignments are justified based on how the reviewed literature promotes the level of implementation of the technology. This is further elaborated in Chapter 7.

3.4 Case Study Preparations

To strengthen the findings of this master's thesis, a case study has been implemented. The transmission analysis software tool Power System Simulator for Engineering (PSSE), Excel and Python were used to evaluate conditions in a grid named "Sørnettet". The geographical area of "Sørnettet" is presented in Figure 3.2. Static simulations were completed in PSSE to emphasise beneficial monitoring aspects within voltage stability. Although the simulations are not time-based, they aim to substantiate parameter needs presented in Section 6.5.

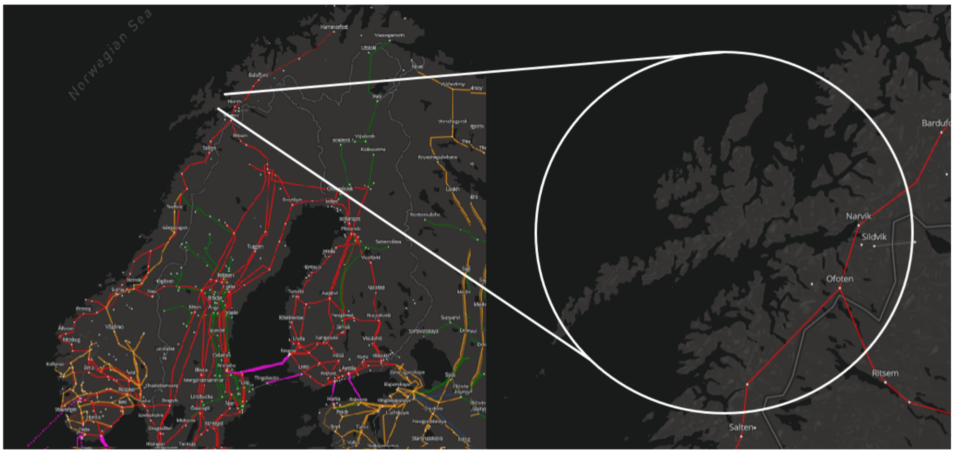


Figure 3.2: Geographical area of "Sørnettet". Adjusted from [19].

Due to power production shortage, "Sørnettet" is dependent on power transmission from the rest of the network. Transmission of power to this area is primarily ensured through three transmission lines, namely "Vestsnittet". Two of the transmission lines are located in a landslide-prone area. Additionally, one of the lines is considered to be in poor condition [20]. As the transmission capacity to "Sørnettet" is exposed to external influences, two hypotheses were investigated:

1. *The PV-curves of a given bus can be affected by an outage of a line.*
2. *The changes are reflected by the voltage sensitivity for the given bus.*

Through the usage of a system model of "Sørnettet", the nature of a selected bus was evaluated through so-called PV curves (presented in Section 6.5). To examine changes inflicted on the bus by external influences, two distinct simulations were considered:

1. **Transmission line *connected:*** Evaluating the bus nature through PV curves based on the connected transmission line (base case).
2. **Transmission line *disconnected:*** Evaluating the bus nature through PV curves based on the disconnected transmission line.

Approximate values for voltage and power were found by solving the simulation model numerically for gradually increasing power demand. These values were collected directly from PSSE. Afterwards, they were saved into a comma-separated values (CSV) file to be retrieved in Python. The Python script is attached in Appendix B. For each simulation (connected **or** disconnected line), only power demand was changed intentionally.

Both simulations resulted in PV curves, which were compared. Additionally, the development of the bus sensitivity is highlighted for the base case. Based on the slope of the curve, it was divided into *lightly*, *medium* and *heavily* loaded. Hence, the sensitivity of the curve could be assessed in three intervals- reflecting the load development. Furthermore, the two distinct simulations were compared based on a common load demand interval. Hence, it was possible to assess the sensitivity change of the selected bus as a result of reduced transmission capacity. In summary, the following points are included:

1. **PSSE:**
    - Usage of system model
    - Increase load demand (MW) gradually
    - Note the resulting voltage level at selected bus
    - Run simulation for operation with connected **and** disconnected line.
2. **Excel:**
    - Insert data from PSSE
    - Save as CSV-file
3. **Python:**
    - Upload CSV-file
    - Plot the PV-curves
    - Assess voltage sensitivity for the base case and the common load region.

4. Background Concepts

4.1 Situational Awareness

4.1.1 Defining Situational Awareness

Through technological advances, information from real-time data is more accessible than ever before. Equipment such as sensors, computers, software, modelling, displays and retrieval systems are constantly improving [21]. An example is PMUs, which will be further discussed in Section 4.4.3. In parallel with increasing human-machine interaction, the control room operators must be aware of how to access and use information. Adapted usage may lead to enhanced Situational Awareness (SA). Endsley defines situational awareness as [22, p. 2]:

> *"The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future".*

Situational awareness eases problem-solving and decision making for control room operators. An extensive flow of information can be processed and interpreted for the benefit of the system. The following three points form the foundation of situational awareness:

- Perception (SA level 1)
- Comprehension (SA level 2)
- Projection (SA level 3).

Perception is about perceiving significant elements in the current environment. Control room operators must have relevant displays and alarms to have a perception of the system state, as it simplifies the process of noticing changes in the system. Comprehension implies extracting the meaning of given data. Operators must be able to have an overall view of evolving situations. In this way, data can be utilised in relation to given objectives. Projection extrapolates information to predict future system states. Future insight enhances decision making.

4.1.2 Visualisation in Relation to Situational Awareness

An operator's decision making and actions are dependent on information access and handling. The foundation for comprehension is laid through a combination of visualisation, critical analysis and reasoning. Well-functioning visualisation tools can ease time-consuming measures and reduce the mental load for operators. The role of visualisation in this interaction can be presented through Naser's statement [21, p. 1-3]:

> *"The goal of visualisation is to enable users to find, focus on, and utilise relevant data and information for the task(s) of concern".*

Visualisation assists humans in extracting information from complex data. Hence, it can be used as a tool to comprehend underlying system states. Figure 4.1 illustrates a hierarchical visualisation concept that can be used to support the three levels of SA. The highest level of data aggregation, or compilation of information, is represented by the top of the triangle. This part contains limited information but informs the operator of the global state of the system- providing perception. The medium level of the triangle includes more details regarding specific system parameters. This section can include displays of trends and parameter profiles- providing comprehension. The bottom part provides detailed information which can facilitate projection of the system state [22].

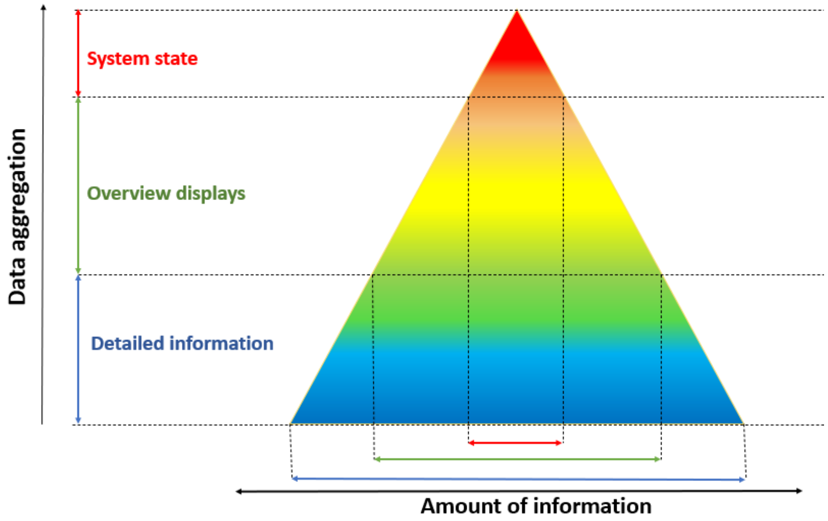


Figure 4.1: Hierarchical visualisation concept. Various degrees of data aggregation corresponds to different amounts of information. Inspired by [22].

Control room operators deal with present system operation. Therefore, one must address what is critical at the given point in time. The capacity of human memory is limited to approximately five to nine elements of information [22]. Consequently, it is critical to successfully achieve situational awareness that the system state is presented with a limited amount of indicators. Although a high level of aggregation is necessary, one must not mask the information too excessively.

Future implementation of user interfaces in control rooms must consider the users ability to navigate in the information space. If an operator loses situational awareness or is prevented from navigating to desired information, the operation may be at risk. Therefore, the following elements are of great importance to keep operators appropriately immersed in the information space [21].

Overview allows the operator to see the greater picture. In certain situations, an overview can provide additional information to the user when propagated to another dimension. For example, 3D visualisations may present details not revealed in 2D.

Zoom enables the operator to navigate to the area of interest. This property must be developed with caution as users must maintain intuitive navigation ability.

Filter excludes unnecessary information that may be at the expense of the operator's focus. These may highlight elements that meet given requirements from the operator.

Details on-demand allow operators to select items they desire more information about. Users are then able to retrieve further information on selected points.

4.1.3 Visualisation Concepts - an Overview

Modern visualisation implies an interaction between user and technology. The user gains insight from representations based on technology and activities. Interaction facilitates adjustments and selection of new portrayals of information. The information is portrayed in a range of dimensions, whereas some are presented in Figure 4.2. Through 2.5D visualisation, a 3D illusion is portrayed on a 2D display surface. Illustrations in 3D include depth, width and height. Through interactive use of 3D visualisation, one may operate with virtual reality. Additional dimensions exist but are often considered too complex for the human mind [21].

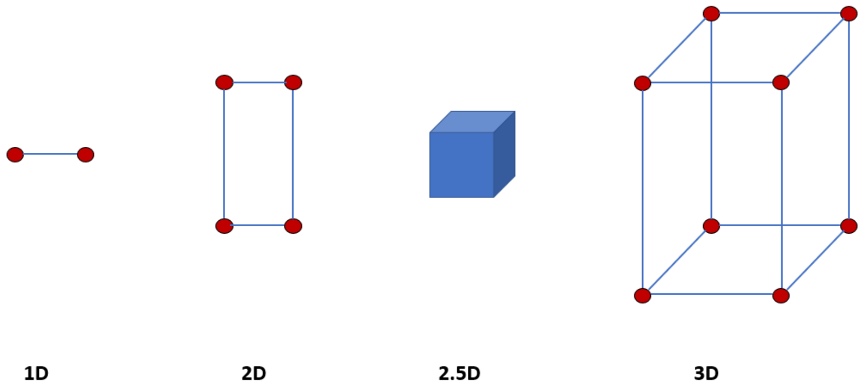


Figure 4.2: Representations of dimensions from 1D to 3D [21].

The human mind is sensitive to asymmetry [22]. Thus, operators can gain intuitive comprehension of system conditions based on symmetrical properties. An example is Kiviat diagrams, illustrated in Figure 4.3. Deviations are represented by asymmetrical properties deviating from approved intervals. In this case, the selected threshold interval is represented by the green line.

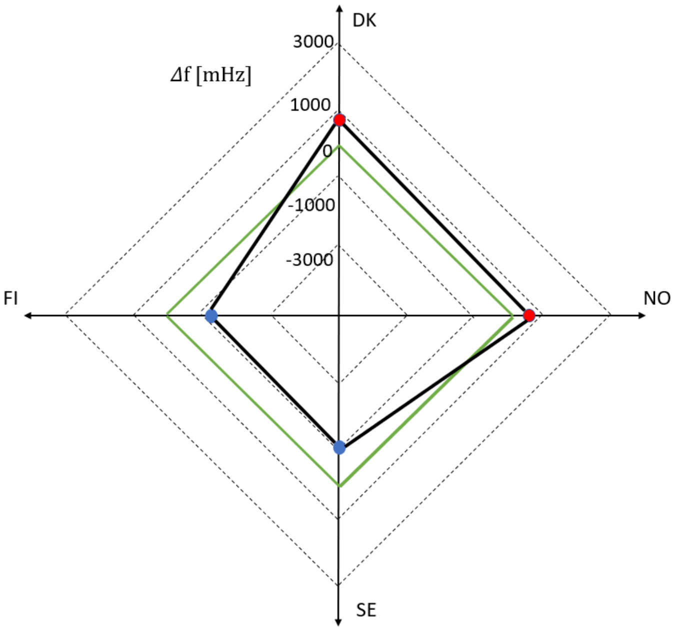


Figure 4.3: Kiviat diagram presenting frequency deviations in the Nordic synchronous area. Inspired and adjusted from [22].

Colouring is another mean to cause a response. Intuitive colour combinations may promote appropriate reactions. An example of intuitive colour renderings is traffic lights. Red lights aim to slow down incoming vehicles, whereas green lights promote movement. Similar colour communication can be done in the human-machine interface. Red colouring may indicate the need for change, whereas blue may require the opposite change for selected parameters. During satisfactory operation, green might be a suitable colour choice. However, conditions such as colour blindness among operators may influence colour choices.

4.2 Power System Stability - an Overview

Power system stability branches into frequency stability, voltage stability and rotor angle stability as presented in Figure 4.4. Both frequency and voltage stability can be short or long term phenomena, whereas rotor angle stability is short term. Short and long term implies that the study period of a particular branch can be given in seconds or minutes, respectively [23].

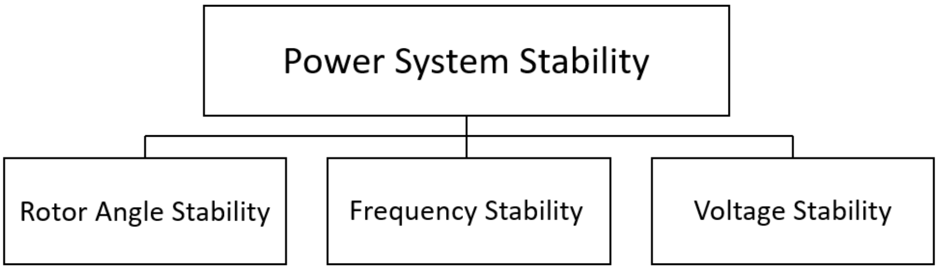


Figure 4.4: Power system stability classification. Adjusted from [24].

1. *Frequency stability* requires maintaining frequency within nominal levels. Instability can cause spinning reserves and rapid starting generators to adjust to the need. Thus, the generation can increase or decrease according to low and high demand. If the response measures take too long or there are inadequate resources, thresholds and time delays may trigger load-shedding relays. That is disconnecting load to lessen the burden on the system. Generator tripping can occur when high frequency persists beyond permitted duration [25]. Frequency instability is often associated with insufficient response measures, inadequate generation reserves, and poor coordination of control and protection equipment [24].

2. *Voltage stability* is closely related to the available power transfer in the network. Consumption exceeding the capable transmission and generation of power can cause voltage collapse. Progressive voltage drops are most common and can lead to load loss and system equipment tripping [24]. Thus, voltage stability relates to the power system's ability to sustain bus voltages after disturbances [23]. During normal operation, consumption should never approach the maximally available power transfer limit. Such cases can occur during gradual load increases or because of contingencies. Contingencies can reduce the transfer capacity so that the pre-contingency demand is not met [26].

3. *Rotor angle stability* depends on interconnected synchronous machines maintaining synchronicity. The absence of equilibrium between input mechanical torque and output electrical torque in the machines causes asynchronous operation. This implies that the rotors of the machines may accelerate or de-accelerate. Such operation can cause rotating phasors (see Section 4.4.3) of current and voltage, which can have an impact on various grid devices [27]. Instability caused by asynchronous operation manifest in increasing angular swings of some generators. Sustained oscillations of increasing amplitude can result in the separation of groups of machines. During asynchronous operation between groups of machines, each group can maintain synchronism within itself [23].

4.3 Power System Security

4.3.1 Defining Power System Security

Due to its extensive and complex nature, the power grid is vulnerable to ramifications. Sudden events such as prompt connection or disconnection of loads can cause rapid transients between operating states [28]. Influences should be mitigated by the system so that the system can comply with various constraints (bus voltages, line flow limits etc.). Grid security is perceived as an instantaneous and time-varying condition, dependent on the robustness of the grid. According to Fulli, grid security is [29]:

> *"The power system's capability to withstand disturbances - i.e. events or incidents producing abnormal system conditions -, or contingencies - i.e. failures or outages of system components - with minimum acceptable service disruption".*

Power system constraints consist of equality constraints E and inequality constraints I [30]. Both constraints can alter the system state during violated operation. Equality constraints relate to the total load and generation of the system, where equilibrium in equation (2.1) is essential. The equilibrium determines whether or not the load demand of the system is met. Inequality constraints refer to the limitations of physical equipment to some variables. This could be the tolerable voltage range at buses, maximum allowed power transfer through lines or line currents. The variables must be operated within specified maximum/minimum levels to avoid damage to system components.

4.3.2 Operating State

The power system is mainly divided into five categories of operating states [30]. Each state is dependent on equality and inequality constraints. Transitions between various states can occur controlled or uncontrolled. Figure 4.5 illustrates the relation between the states. Red crosses represent indication of violations of constraints. Additionally, uncontrolled state transitions are highlighted in red, whereas controlled state transitions are green.

Normal operation implies an absence of constraint violations. Thus, the existing load demand is met, and the equipment is not overloaded. Reserve margins are highly correlated to this state. During normal and secure operation, the reserve margins (of transmission and generation) are sufficient to ensure an adequate level of security graded by the load of the lines. Reserve margins could imply the difference between actual line power flows and the corresponding line capability. Margins below given threshold values increase the probability for system disturbances. This initiates the alert state, an insecure state.

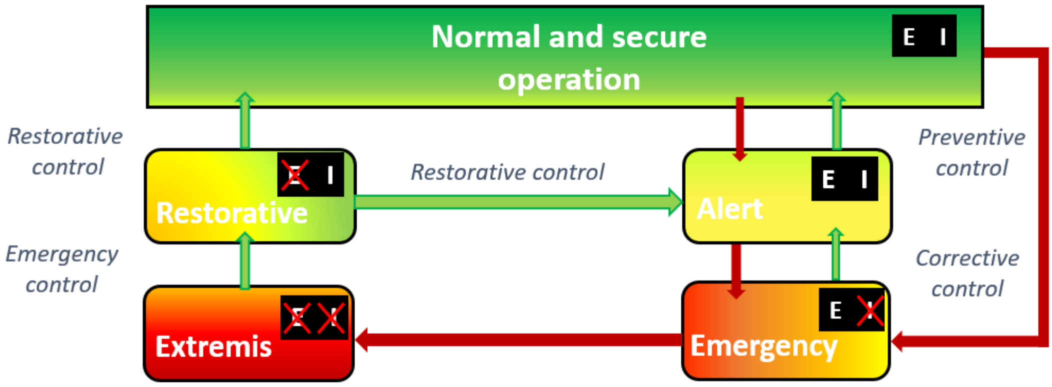


Figure 4.5: Power system operating state classification. Indication of violation is provided for for equality (E) and inequality (I) constraints. Inspired by [30].

Although constraints are not violated, preventative measures must be implemented to return to secure operation.

Disturbances occurring during insecure operation can cause a state of emergency. The system is still intact, but inequality constraints are violated, and system security is breached. Corrective measures can restore the system to an alert state. Delayed or ineffective measures in combination with a severe initial/subsequent disturbance can cause system fracturing. As system splitting and/or load losses occur, the system enters the state of extremis. The restorative state gathers the fractions of the system to reconnect it. Implementation of restorative control actions can re-synchronise the system. Thus, the operation can transition to the alert or normal state depending on the situation.

4.3.3 Security Assessment

Decision making is based on various security assessments of the grid. Security assessment can be divided into three levels [31]:

- **Security monitoring:** Examines whether desired operating conditions are maintained through equality and inequality constraints. *Normal* or *abnormal state.*
- **Security analysis:** Examines whether the system is capable of withstanding selected plausible disruptions. *Secure*, *insecure* or *breached.*
- **Security margin:** Examines the relation between a given operating condition and the limit for secure operation. *Reserve margin.*

Two main categories for analysis methodologies exist, namely static and dynamic. Static security assessments (SSA) are based on steady-state analysis of post-contingency operation. Consequently, one assumes the absence of any instability phenomena affecting the system between pre and post-contingency. Static methods aim to verify bus voltages and line power flow limits for the post-contingency operating state. An example of static security analysis is the N-1 criterion. This implies that the grid (consisting of N components) should be capable of withstanding outage of a major electrical component without compromising electricity supply [32].

Dynamic security assessments (DSA) involve analysis of stability and quality of the transient process between pre and post-contingency. Here, the system is considered to change constantly. Dynamic methods aim to secure stable operation after an occurred contingency and reduce the impact on the quality of service. Thus, the system should damp transients caused by the contingency and reduce their amplitude. Several stability aspects affecting the dynamic nature of the power system are taken into consideration.

4.4 Online Assessment of System State

4.4.1 Online Dynamic Security Assessment

Historically, security assessments have been performed offline based on power flows and time-domain simulations. However, for each change in the system state, new stability limits occur. As the stability limits are not fixed, they are said to change with system loading, voltages and topology. Thus, online dynamic security assessment is beneficial. The assessment utilises a snapshot of the system provided by equations describing the current system state. The process can be divided into [31]:

1. **Contingency screening:** Screening of system snapshot to detect potential problems caused by contingencies.
2. **Contingency evaluation:** Assessing the potential problems to given DSA security criteria.

Dynamic security assessment criteria are usually set based on the following:

- *Stability:* Loss of rotor angle, voltage and frequency stability
- *Voltage excursions:* Dip or rise beyond specified threshold and duration
- *Frequency excursions:* Dip or rise beyond specified threshold and duration
- *Relay margin criteria:* Relay margin violation beyond maximum duration
- *Minimum damping criteria:* Post-disturbance exhibited oscillation damping.

Post-processing, DSA reports the results of the analysis and raises alarms when detecting security issues. Continuous computations performed at sufficient speed makes it possible to trigger automatic control promptly. Additionally, it allows more time for operators to act on contingencies which could lead to potentially insecure operation. The architecture of online DSA varies, but typical components are presented in Figure 4.6.

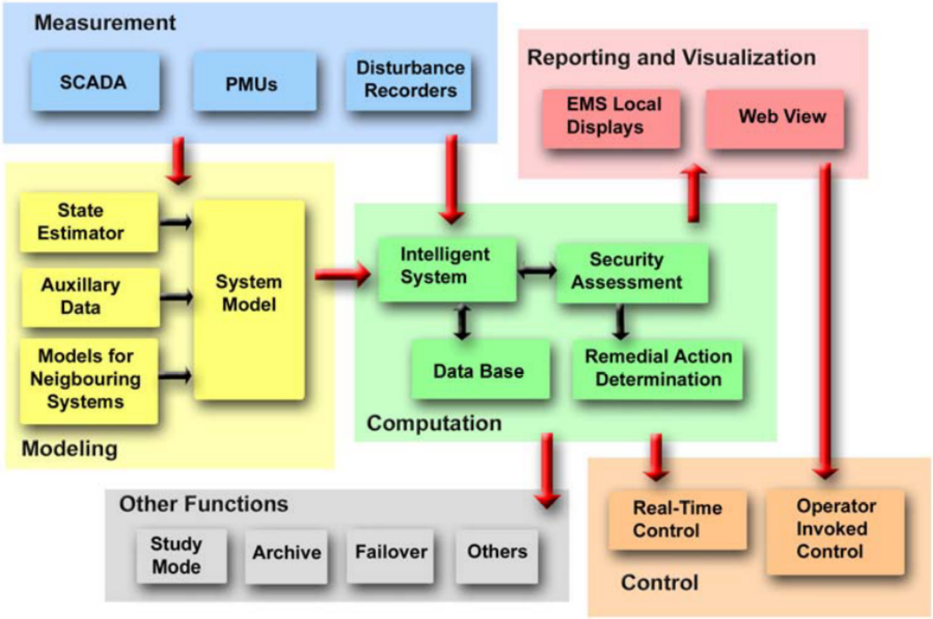


Figure 4.6: Online DSA components presented by Cigre [31].

4.4.2 Controllability and Observability

The system state of a physical power system can, according to Andrei, be defined as [33, p. 23]:

> *"A collection of numbers completely describing the system model at a certain time ("snapshot")".*

Several possible system states exist, given by a total of S states. Various parameters referred to here as input values affect several system states. The influenced states are denoted M. An input value could be electrical power influencing the physical system. Figure 4.7 illustrates a relation between input values and observable values. An observable value could be the system frequency.

Measurable quantities, such as sine voltages, may reveal information about the present system state. There might be a limited amount of system states, N, influencing the measured quantities. The measured quantities affect the observable function. An observable function could be the Root Mean Squared (RMS) value of sine voltage. L denotes shared states between M and N. Consequently, these L states are affected by input values as well as affecting the observable value [33].

The observability O of a system state can be assessed through equation (4.1). During situations where an observable value corresponds to a great number of system states,

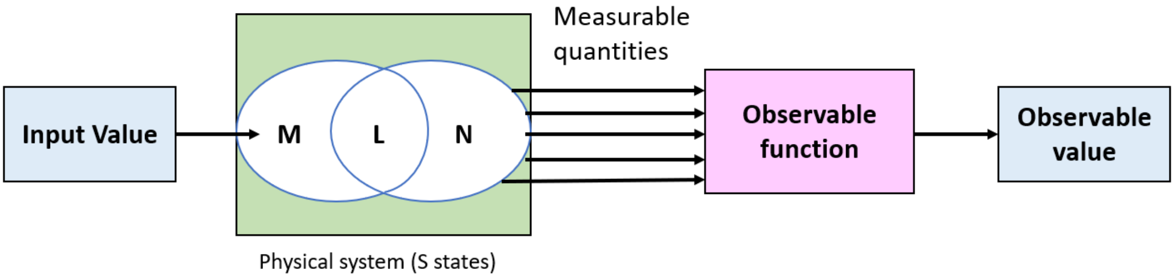


Figure 4.7: The figure presents the relation between input signals in a physical system and observable values. Adjusted from [33].

there is little observability of the actual state of the system model. In the case of full observability, the observable value would only be linked to one system state, giving N equal to one. Consequently, the observable would provide reliable information of the actual system state.

$$O = \frac{1}{N}, \qquad \begin{cases} O << 1 & \text{No reliable information of system state.} \\ O = 1 & \text{System model fully known.} \end{cases} . \tag{4.1}$$

The controllability C of the system is assessed through equation (4.2). In cases where the input value does not influence the observable value, L will be zero. Then the system can not be controlled based on the observables at hand. In situations where the physical input greatly impacts the observable value, C will be close to one. Thus, the system can be controlled comprehensively.

$$C = \frac{L}{M + N - L}, \qquad \begin{cases} C << 1 & \text{System can not be controlled.} \\ C = 1 & \text{System can be controlled.} \end{cases} \tag{4.2}$$

4.4.3 PMU and SCADA

Phasor Measurement Units measure quantities such as voltage and current at substations in the electrical grid. Additionally, PMUs can derive parameters such as frequency and phase angles [34][35]. Phasors represent the sinusoidal nature of the measured quantities at a specific point in time. They are complex numbers consisting of a particular magnitude and phase angle of a sinusoidal measurement. For instance, the phasor voltage magnitude can be represented as the RMS value given by

$$V_{rms} = \frac{V_{max}}{\sqrt{2}}. \tag{4.3}$$

Here, V_{max} represents the peak value of the sinusoidal voltage. Furthermore, V_{rms} in combination with the phase angle δ can express the rms phasor $\boldsymbol{V_{rms}}$. Equation (4.4) presents the phasor in exponential and rectangular form

$$\boldsymbol{V_{rms}} = V_{rms}e^{j\delta} = V_{rms}cos\delta + jV_{rms}sin\delta. \tag{4.4}$$

In equation (4.4) j denotes an imaginary number, namely $\sqrt{-1}$, making it a complex form [36]. Figure 4.8 illustrates the sinusoidal waveform, including the parameters V_{max}, V_{rms} and δ. The associated phasor diagram is also presented.

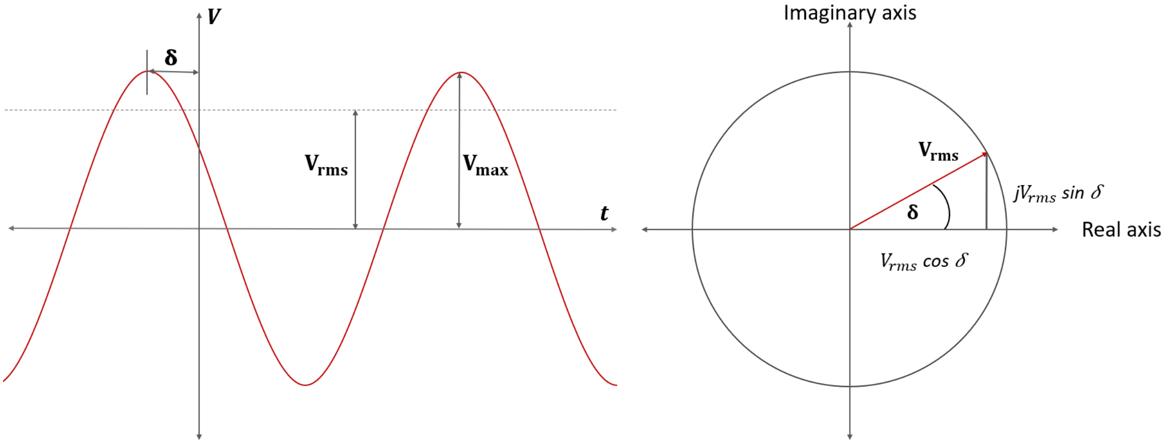


Figure 4.8: Voltage phasor using RMS-value of a sinusoidal waveform [37] [36].

Global positioning system (GPS) clocks are frequently used for time-stamping phasors. Measurements from several devices are then time-synchronised. This process has an accuracy finer than a microsecond [38]. Phasor data from various substations can then be compared. Phase angles are often provided relative to a reference bus as in Figure 4.9, whilst angle differences consider the relation between them.

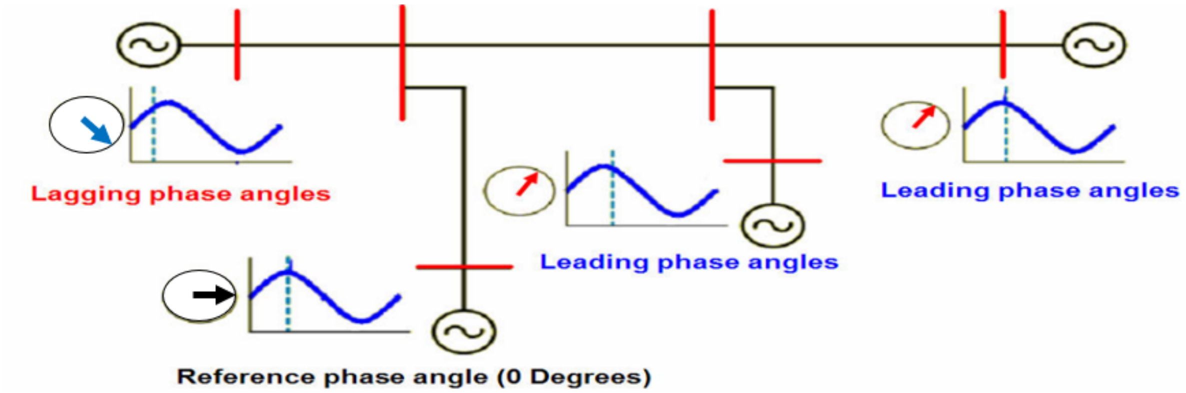


Figure 4.9: Relative and reference phase angles. Adjusted from [39].

Traditional equipment like Supervisory Control and Data Acquisition (SCADA) also measures voltage and current phasors. However, these do not have the same level of time resolution, nor are they time-synchronised. PMU data is typically obtained at a rate between 30 - 60 records per second. The frequent measurements offer a dynamic representation of the system. In comparison, SCADA measuring devices generally report every four to six seconds [38]. Figure 4.10 compares measurements from both sources.

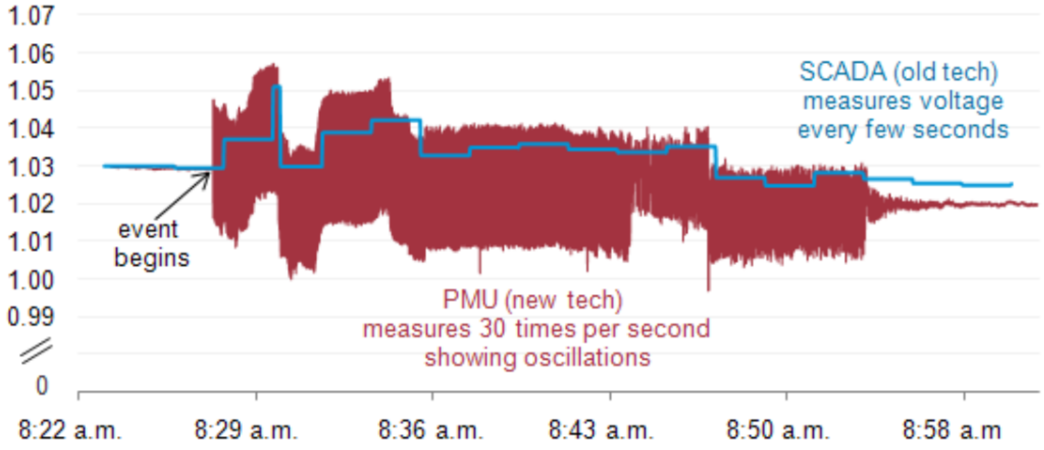


Figure 4.10: Voltage magnitude measurements compared through data from PMU and SCADA [40].

Presently, Statnett has 120 PMUs, and another 60 are planned to be installed. Additionally, there are about 145 other devices in the Nordic synchronous area [41].

The valuable real-time insight provided by PMUs can be utilised for a variety of grid operations. It can enhance the transparency of the entire interconnected system and enhance situational awareness for system operators. Production of PMU data is rapid, and hence voluminous amounts of data must be processed for analysis and visualisation. Reliable and rapid communication is crucial for successful real-time applications [42]. Detection and prevention of emerging situations can become more manageable with increased insight into the grid.

4.4.4 Wide Area Monitoring System Based on PMU

State estimation can be improved by the rapid and frequent nature of PMU data. However, not all operating states are dependent on these properties. During normal and secure operation, SCADA provides adequate speed and resolution to monitor the system state. Signal processing and data transfers cause additional processing time for PMU data. Hence, conditions that require swift reaction time must be handled by local protection and control devices. Figure 4.11 reveals that wide-area monitoring systems based on PMU data provide great potential for detecting and correcting events in the emergency and alert state. Such an implementation facilitates early detection and prevention of arising system events [28]. Thus, PMUs can be perceived as an enhancement of the current monitoring and control system.

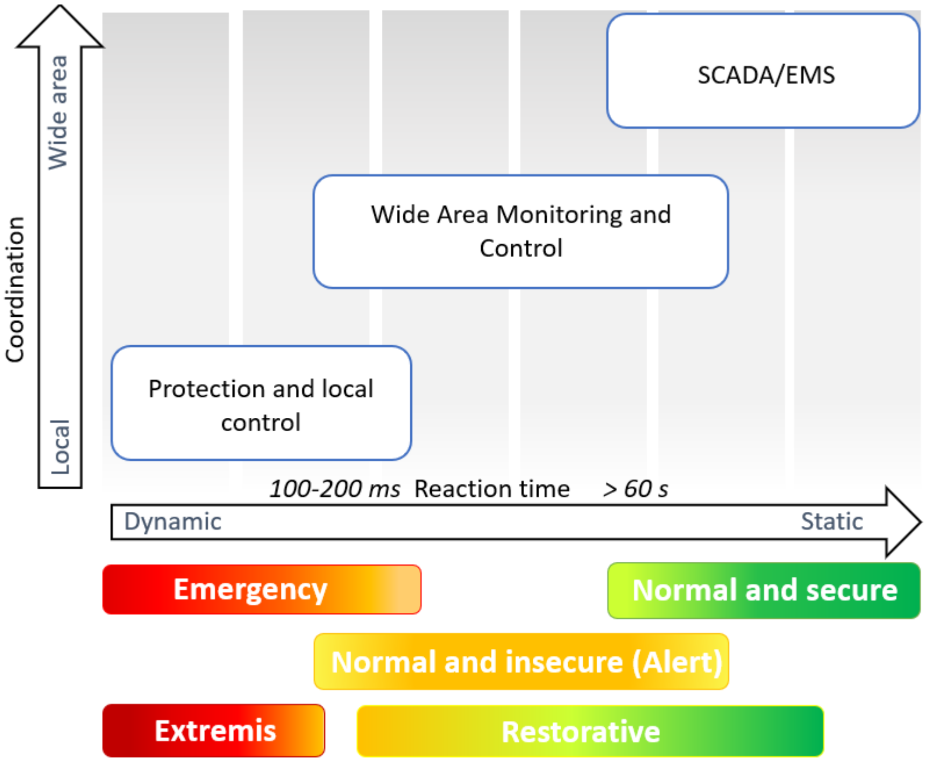


Figure 4.11: Comparison between scale of coordination and reaction time for various protection, monitoring and control equipment [28].

5. State-of-the-Art Observability

The Norwegian power system is branched into a transmission, regional and distribution grid. Statnett is responsible for operating the transmission grid, which is the network with the highest voltage. More precisely, the voltage level is usually set between 300 - 420 kV. Some areas are even administered at 132 kV. In total, the length of the transmission system is about 11 000 km. Usually, large electricity producers and consumers are connected to the transmission grid [43].

Statnett consists of three control centrals: the national central office (*Landssentralen*) and two regional centres (*Regionsentralene*). Both the national central office and one of the regional centres are located in the south of Norway. The second regional centre is located in the north of Norway [44]. Figure 5.1 depicts the national central office.

Figure 5.1: The national central office (*Landssentralen*) at Statnett [45].

5.1 Highlights from the Interviews

Complete interview notes from the first and second interview within real-time control room operation can be found in section E.1 and E.2, respectively. Highlights from both interviews will be further reviewed in this section.

The present monitoring scope at Statnett consists of SCADA input, administrative information, weather data, lightning activity and information that is dialled in over the telephone. Occasionally, an operator can have as many as 150 telephone calls within nine hours. The telephone calls may deal with observed deviations in the field. Administrative information includes information regarding electrical safety, maintenance as well as contact information such as telephone numbers and e-mail.

Statnett has the coordination responsibility in the power system. Therefore, they can request information from all licensed participants in the grid. Participants such as producers and power plants may not have measurements of the same quality as Statnett.

The current alarm system typically consists of four levels, which range from alert to critical. Events that do not impede operation can also trigger alarms. Thus, alarms can be perceived as distracting. In these situations, operators sometimes disconnect the alarm system and retrieve information from other sources. Major errors can lead to four to five pages of alarms on the operators' screens. Alarm messages could for example indicate "circuit breaker switched off" or "voltage-free area".

Present detection of events and faults are to a certain degree based on the operator's "clinical perspective". Present detection of oscillations, islanding and voltage instability relies on this internal knowledge. Islanding is nevertheless considered to be detected relatively quickly, according to the interviewee. PMU data is desired as it provides high resolution so that operators can observe system changes. The utilisation of PMU data and its useful applications are considered absent as of now in the control room, partly because situations have arisen elsewhere than the locations of the PMUs. Implementation requires thorough testing for operators to gain confidence with the technology.

Many control measures are remotely implemented. Examples include switching connections and parameter levels. During fault situations, human intervention is often required. Such measures are carried out by field crews. During these situations, electrical safety is highly prioritised. Control room operators have the responsibility to ensure safety throughout (e.g. through work shifts).

Future development of control rooms should consider the current information overload. Operators are dependent on a more dynamic system as operation and challenges change continuously. The structure across operators' screens should be identical. It must also be flexible and recognisable. Real-time detection of events is preferable.

5.2 Information Access at Statnett

Operation in the national central office is mainly based on global system entities, such as system frequency. Regulation of production and prevention of overload in the system is essential. The national central office regulates bottlenecks in the grid. Bottlenecks arise when transmission needs surpass transmission capacity. The regional central offices operate closely with local entities, such as voltage. Statnetts' stations and lines are mainly monitored by the regional centres. Responsibilities include electrical safety and restoration post-disturbance [44].

Real-time network constraints may reduce the operating efficiency and should therefore be detected and managed. Threats to operational safety may include faults, transmission limitations, transmission outage and load transfers [46]. Figure 5.2 illustrates the number of operational disruptions at Statnett and triggering causes for 2018 and previous years. Ambient conditions, technical equipment and human interaction appear to be the most frequent causes for operational disruptions [47].

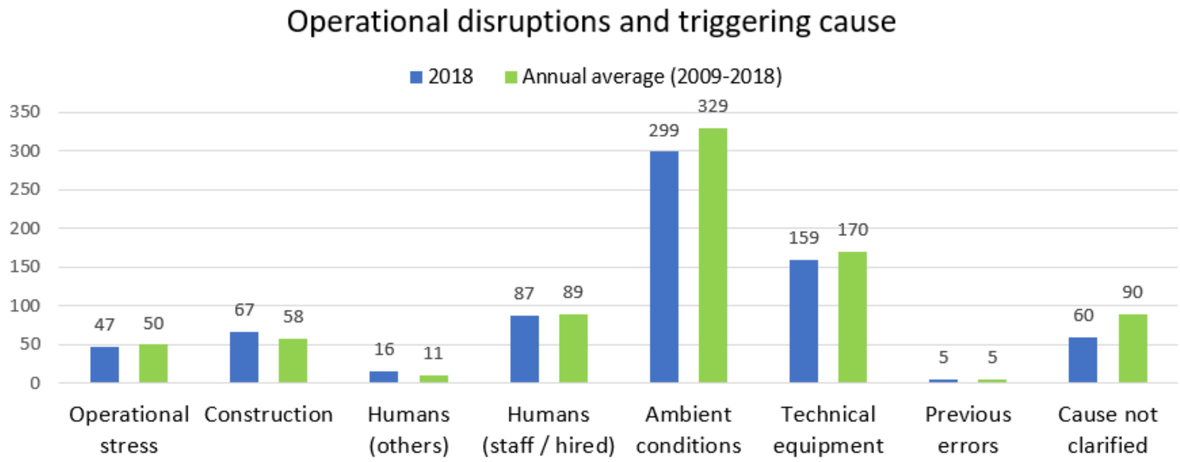


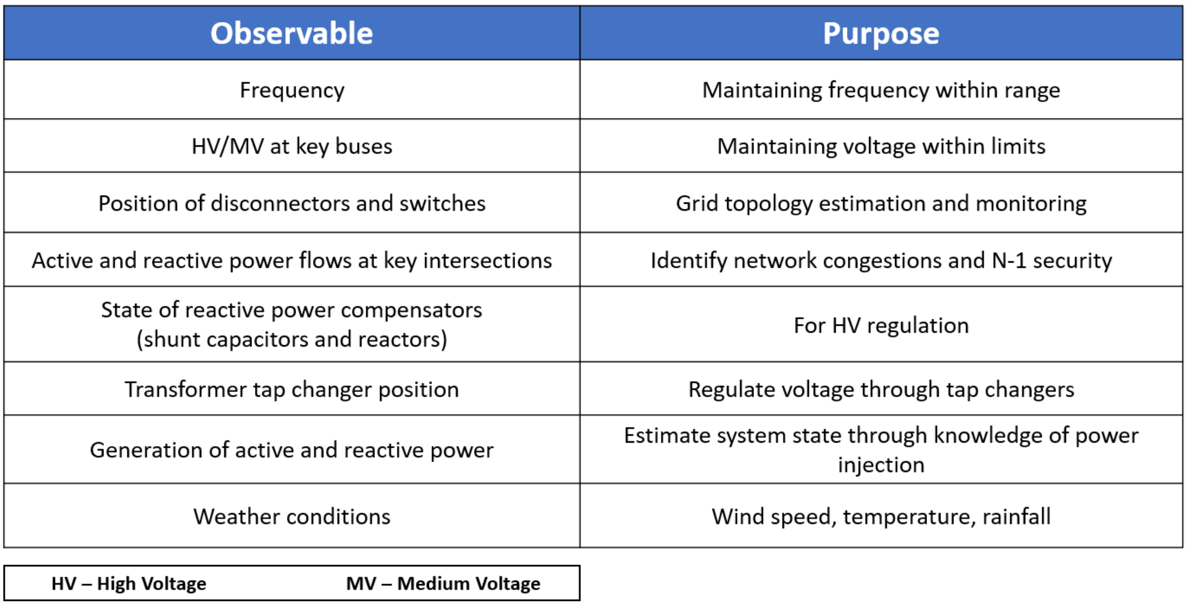
Figure 5.2: Operational disruptions and causes at Statnett. Adjusted from [47].

About 70 % of the operational disruptions at Statnett are considered possible to analyse automatically. Machine learning provides possibilities for prediction and automation of manual tasks [48]. Operators at Statnett benefit from an error analysis tool named AutoDIG. Line failures could entail information within AutoDIG such as time, suggested fault location, wire length and fault type. Additionally, lightning activity and geographical coordinates are reported. Dynamic ambient weather conditions such as wind, rainfall and temperature are also provided [49].

Figure 5.3: Information flow into the power system control room [50].

Around 200 million measurements are produced annually at Statnett [48]. The control room information flow categories are presented in Figure 5.3. The majority of the sensors are located within, or close to, transmission elements such as circuit breakers and power transformers at substations [51]. Current state-of-the-art observability for TSO operation in Europe includes the parameters presented in Table 5.1.

Table 5.1: The table presents state-of-the-art observables in the power grid, aimed at TSO operation in Europe. Adjusted from [33].



Observable	Purpose
Frequency	Maintaining frequency within range
HV/MV at key buses	Maintaining voltage within limits
Position of disconnectors and switches	Grid topology estimation and monitoring
Active and reactive power flows at key intersections	Identify network congestions and N-1 security
State of reactive power compensators (shunt capacitors and reactors)	For HV regulation
Transformer tap changer position	Regulate voltage through tap changers
Generation of active and reactive power	Estimate system state through knowledge of power injection
Weather conditions	Wind speed, temperature, rainfall

HV – High Voltage **MV – Medium Voltage**

5.3 Discussion

From Section 5.2, extensive parts of control room operation are considered possible to automate. In the long run, this could reduce the cognitive load for the operators. However, human expertise is still required. The operators must be provided adequate tools to ensure system security. This applies, for example, to oscillations and islanding events. The current SCADA system is considered insufficient to maintain situational awareness for future system developments. PMUs are on the other hand considered to be future-oriented solutions. However, Statnett has already mounted PMUs that are not used by the control room personnel. The interviewee stated the reason could be that errors do not necessarily occur at the PMU mounting locations. Thus, it seems to be a need for either several PMUs or more emphasis on the mounting locations.

The transition from traditional to modern monitoring tools can be substantial and challenging for control room personnel. Control room personnel are perceived as somewhat conservative to new solutions. According to the interviewee, the scepticism is because they are completely dependent on being able to master the solutions. As real-time operation demands rapid and precise responses, there is no room for trial and error. Both the interviewee and ENTSO-E emphasise the need for control room personnel training. It is important to make the transition to future solutions as intuitive as possible, both regarding the training of the operators and testing of applications.

Alarms aim to draw attention and make the observer observant of an event. However, alarms seemingly have the potential to alter the operators' focus. It is not beneficial that operators at Statnett avoid the alarm system, to focus and retrieve information about an event. Thus, it appears as if the design of alarms should receive more focus in future development, both in terms of content and design. For example, it seems useful with fewer alarms that rather present the full scope of a situation.

Future operation will be more prone to the fluctuating nature of RES production. At present, personnel at Statnett can obtain information from producers and power plants on demand. However, it is stated that these measurements are not necessarily of high quality. Enhanced data quality and information flow across institutional levels could enable closer collaboration regarding production and coordination.

ENTSO-E emphasise that decarbonisation is dependent on the security of supply of electricity to all Europeans (see Section 2.3). Based on Figure 5.2, there is a potential to reduce the number of operational disruptions related to ambient conditions and technical equipment. More extreme weather is considered probable due to climate changes. Thus, there might be an increased need for field asset monitoring to operate the grid. Field asset monitoring can then potentially increase situational awareness in the control room. This applies to both ambient conditions and technical equipment. Thus, the need for field asset monitoring is also examined in future data needs in Chapter 6.

Present control room operation relates to reported maintenance and faults where staff must be organised to implement remedial measures. The latter unfolds opportunities within remote collaboration between, for example, field crews and control room operators. Present communication across disciplines is dependent on telephone calls and e-mail. These channels do not necessarily enable rapid and precise reporting. Collaboration with field crews should be highly prioritised to sustain personnel and system security. It is crucial to indicate correct system conditions for safe operation. Hence, it can be beneficial to streamline, simplify and improve the present communication channels. This could save time, resources and reduce the risk of accidents. Therefore, solutions within remote inspections and collaboration are explored in Chapter 7.

6. Real-Time State Indicators

Applications using synchrophasor data have the potential to ease recognition and response to evolving grid events for operators in power system control rooms. Online applications can provide information that reveals essential system changes. Situational awareness in the control room depends on the sensor data and analyses reaching the operators promptly. The operator or the automatic system must also be able to process the information and respond in time. Future observability and controllability elements are presented in Table 6.1. Several modern observability aspects are reviewed in the following sections.

Table 6.1: Traditional and modern attributes for observability and controllability in the power system. Adjusted from [51].

Traditional		**Modern**	
Observability	**Controllability**	**Observability**	**Controllability**
Static Slow Local view	Reactive High-level control	Dynamic Fast Global perspective	Predictive System-wide coordination
	Eliminate or avoid risk		**Manage risk**
▪ Weather ▪ Flows on key lines ▪ Voltages on key buses ▪ Connecting line flows ▪ Line status ▪ Generator status ▪ Real-power output ▪ Predictable seasonal flow patterns	▪ Balancing and load-following ▪ Discretized demand response ▪ Transmission limit determination from simulation studies	▪ Grid stress ▪ Grid robustness ▪ Dangerous Oscillations ▪ Frequency instability ▪ Voltage instability ▪ Reliability margin ▪ Field asset information	▪ Generator coordination ▪ Topology ▪ Flow control ▪ Demand-side coordination

6.1 Frequency Stability Monitoring

The nominal frequency level is 50 Hz in the Nordic synchronous area, whereas operators aim to maintain an interval of 49,9 Hz - 50,1 Hz. As the case described in Figure 6.1 shows, frequency dips are good indicators of generation loss, whereas frequency rise may indicate load trips. The ripple effects vary in distinct locations. Hence, operators can reveal generation drops through rapid frequency declination in nearby substations. The Rate of Change of Frequency (ROCOF) can thus aid identification of the location and extent of an event [52].

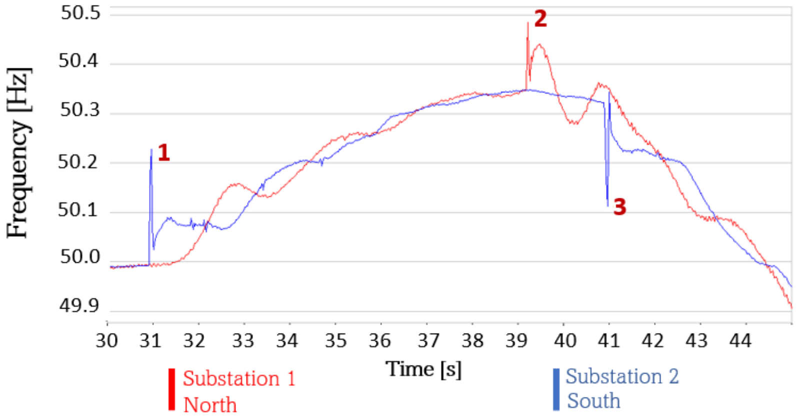


Figure 6.1: Frequency variation detected through PMUs in Noway [53].

Figure 6.1 depicts PMU data from substations in the north and south of Norway. At Point 1, a trip of HVDC south in Norway causes an increase in frequency at both substations. The decreased power export causes the frequency rise. Load trips occur in the north (Point 2) due to the high frequency, with an insignificant impact on the south. The rapid disconnection of loads causes a steep frequency rise. The reintroduction of the HVDC ramps causes a rapid frequency drop in Point 3. In other words, the frequency drops due to increased transmission of power in the south [53].

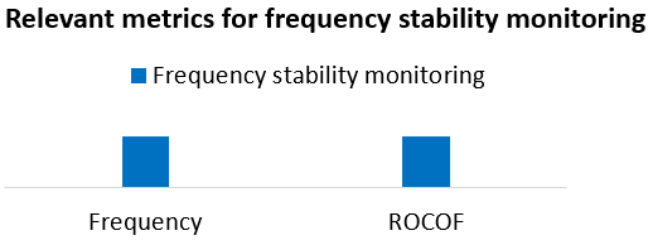


Figure 6.2: Relevant information related to frequency monitoring.

Figure 6.2 summarises relevant metrics related to frequency stability monitoring. Note that the representation does not illustrate an aspect ratio but rather whether the monitoring benefits from the specified parameters. This representation method is used to summarise data needs throughout this chapter.

6.2 System Separation and Re-synchronisation

Islanding implies electrical isolation of a part of the power system, energised by local energy sources [54]. Unintentional islanding can increase the risk of voltage, and frequency deviations caused by an imbalance between power demand and resources [55]. Furthermore, islanding can increase the risk of injury to personnel who handle its restoration [56]. Islanding is the name for [28]:

- Separation of a large interconnected system
- Splitting of power system into several islands
- Separation of a significant portion of the power system
- The separation of a single generator.

During islanded operation, local generators supply associated loads with power. Mahat states that: "*if the change in loading is large, then islanding conditions are easily detected by monitoring several parameters: voltage magnitude, phase displacement, and frequency change*" [54, p. 2744]. Bus frequencies and voltage (magnitudes and angles) from an entire interconnection can thus be presented to operators and aid in detecting islanding events. This results in three methods for detecting unintentional islanding, namely:

1. **Frequency-based detection:** Inconsistent levels (e.g., 50.5 Hz and 49.5 Hz) at distinct parts of the grid, remaining discrete over a specific duration, indicates system separation. Due to the system being isolated, the frequency can differ from the main utility grid as a result of resource and demand imbalance [57][38]. ROCOF can be used to monitor the frequency development [58][59].

2. **Voltage magnitude-based detection:** Imbalance between resource and demand drives voltage deviations in the island [55]. Thus, voltage magnitudes can reflect system changes upon an islanding event.

3. **Voltage angle-based detection:** Generally, the phase angle of an island drifts away from the main grid due to load changes [60]. Thus, phase angles can indicate that an islanding event has occurred [35]. The development of the phase angle can be monitored through the rate of change of voltage angle differences [28].

Furthermore, several methods to detect islanding events exist, some of which are discussed in [54]. Rapid islanding detection could be enhanced through, for example, usage of the Rate of Change of Output Power from the island (ROCOOP, given by $\frac{dP}{dt}$). The ROCOOP would be greater post- than pre-islanding for corresponding load changes. Hence, it can reflect the change of output power of an island and aid detection.

The re-connection of an island to the main grid can potentially cause destructive fault currents and large mechanical torques, which can harm rotating generators [55][56]. Re-synchronisation is simplified through phasor data. Frequency, voltage and angles (on both sides of the separation) should be approximately at the same level during re-synchronisation. The phase angle difference must be within a safe interval. These parameters provide operators knowledge of the appropriate time to close circuit breakers for successful re-synchronisation [61]. Closure within given angle intervals reduces the risk of power instability as equipment and loads are reintroduced correctly [62].

Relevant metrics related to islanding and re-synchronisation is presented in Figure 6.3.

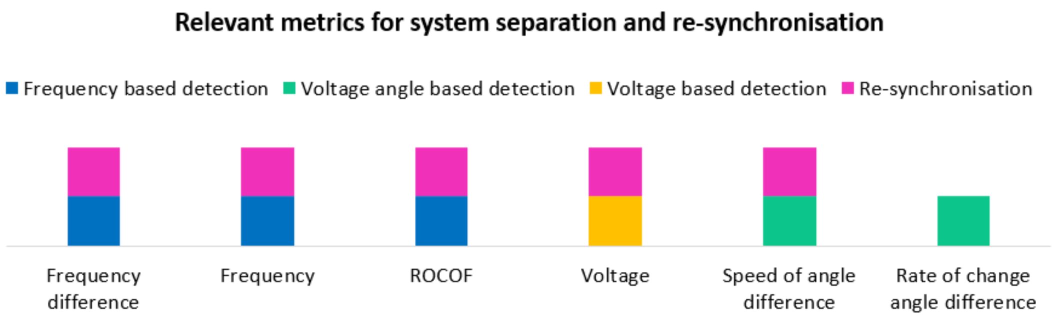
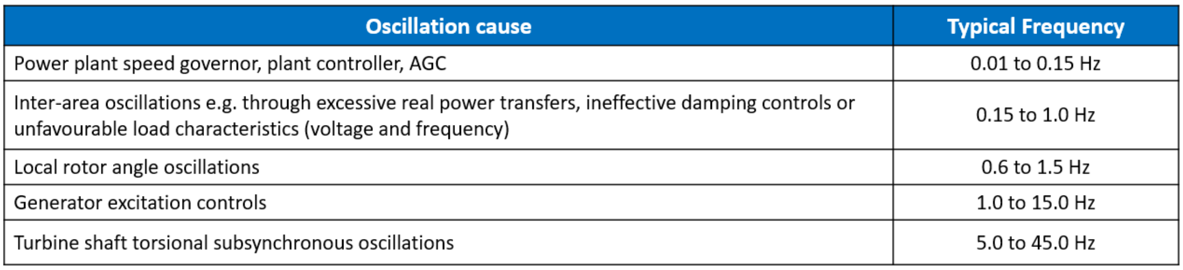


Figure 6.3: Relevant information related to islanding monitoring.

6.3 Oscillation Detection and Source Location

Oscillations are unintended periodic exchanges of energy across power grid components. They appear as cyclical changes in voltage or current. The main categories are *natural* and *forced* oscillations [63]. Natural oscillations are considered normal following variations in the power system. Various grid equipment contributing to natural oscillations results in distinct frequencies. Some of these are presented in Table 6.2. Dynamic power system properties that contribute to the natural oscillations can be described through so-called oscillatory or electromechanical modes. As the modes are closely related to system responses, control measures demand adjustment of system operation [64].

Table 6.2: Typical oscillation causes and frequency [63].



Oscillation cause	Typical Frequency
Power plant speed governor, plant controller, AGC	0.01 to 0.15 Hz
Inter-area oscillations e.g. through excessive real power transfers, ineffective damping controls or unfavourable load characteristics (voltage and frequency)	0.15 to 1.0 Hz
Local rotor angle oscillations	0.6 to 1.5 Hz
Generator excitation controls	1.0 to 15.0 Hz
Turbine shaft torsional subsynchronous oscillations	5.0 to 45.0 Hz

Forced oscillations are closely linked to the periodicity of the system load and generation. They manifest in power, frequency and voltage deviations. Narrow frequency components and harmonics characterise them. Forced oscillations are not divided into particular frequency ranges. Their shape can be observed through amplitudes and phase angles in various parts of the grid. In general, forced oscillations reveal nearly constant amplitudes. Thus, it can be challenging to separate them from marginally stable natural oscillations [63]. Sustained forced oscillations can be corrected by disabling the input. The input could be a variety of sources, some of which are presented below [64]:

- Traditional generation (e.g. hydro and nuclear plants)
- Renewable generation (e.g. wind and solar)
- Cyclic load (e.g. aluminium smelting)
- Malfunctioning controls.

The energy in a power oscillation indicates whether the oscillation is growing or dispatching (increasing or decreasing amplitude, respectively). An increase in energy implies more oscillatory activity [34]. Excessive oscillations may result in undesirable events such as equipment damage or instability. Stability mainly depends on generators, load characteristics, the operating point, and the structure of the power system [24].

Grid robustness is the grids ability to deal with system events (e.g. through damping). Damping can be assessed through relative frequencies on both sides of an oscillatory mode [58]. The electromechanical modes are well damped and stable if oscillation amplitudes are reduced to nominal values based on stability assessments (e.g. 8-15 % damping). However, negative damping causes increased oscillatory activity. Damping can be limited when the system is subjected to stress. Damping should not fall below 5 %, whereas levels below 3 % demand urgent corrective actions [52]. Low damping could also indicate the presence of a forced oscillation with nearly constant amplitude [64].

The oscillatory modes consist of set frequencies and damping coefficients for different types of natural oscillations. These are often classified as local or inter-area. Local modes are most commonly encountered and involve one generator (or several within one power plant) that swings in opposition to the remaining grid. Generally, the mode frequency is in the range of 1-2 Hz. Inter-area oscillations occur when groups of generators in distinct areas swing against each other, normally with mode frequency between 0.1-1 Hz (with reference damping of at least 5 %). Generally, the time frame of occurrence for inter-area oscillations is around 1-20 s [24]. Inter-area electromechanical oscillations can be caused by weak links between power systems or local challenges related to system operation [28].

Information needs can be provided based on the following purposes [28]:

1. **Low-frequency oscillation detection:** Detection of local and inter-area oscillatory modes. Requires amplitude, frequency and damping of the detected mode.
2. **Oscillation source location:** Analysis of the location/source of the oscillation. If PMUs are installed at generator(s), responsible generator(s) are located. Otherwise, PMUs disclose the direction toward responsible generator(s). Requires active and reactive power, power system frequency and voltage angle differences.

Control room personnel should be informed of whether a natural or forced oscillation is present. The potential source of the forced oscillation should also be presented to implement control measures. Figure 6.4 summarises relevant metrics to detect and localise natural oscillations.

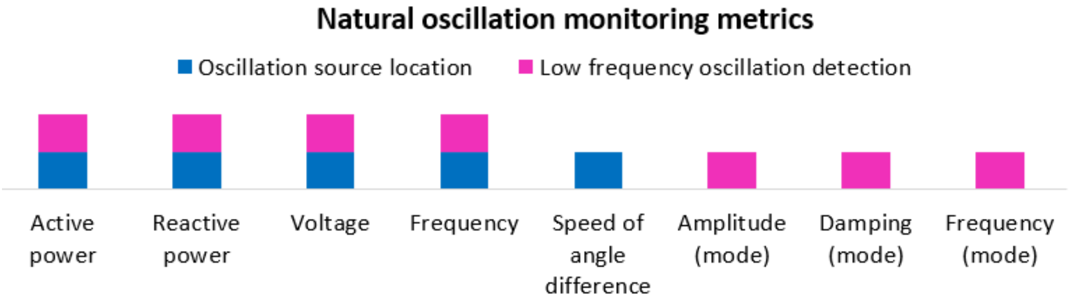


Figure 6.4: Relevant information related to oscillation monitoring.

6.4 Grid Stress Monitoring

Grid stress relates to how power lines are “stressed” to meet up with system loading. Traditionally, system stress has been assessed through power and/or line current. Both measurements are considered local and thus not suitable for wide-area monitoring [65]. Synchrophasors enable monitoring of phase angle separation between measuring locations. Phase angle separation provides operators with a good indication of grid stress. An excessively stressed grid, characterised by significant angular differences, can alter system stability. Large phase angle separation particularly applies to large grids with great inter-area power transfers. Greater power flow between the source (high voltage phase angle) and load (low voltage phase angle) causes larger phase angle differences [66].

Grid stress can be increased by rapid changes in the system, such as line outages and increased transmission path loading between source and load. A high rate of change of phase angle differences may indicate an increase in system stress [58].

During events such as the outage of a line, the power transfer may remain unchanged, but the phase angle can change between the relevant buses. Figure 6.5 illustrates this concept. Here, a generator (Bus 1) provides power to a load (Bus 2) through two transmission lines. For simplicity, the system is considered lossless. Both lines have ratings at 2500 MW but deliver 1200 MW each. Consequently, one line can still deliver a total of 2400 MW after an event such as line tripping. However, the phase angle difference between bus 1 and 2 changes from 30° to 90°, indicating increased system stress [65]. Consequently, voltage phase angle differences provide valuable insight into system stress and topology [37].

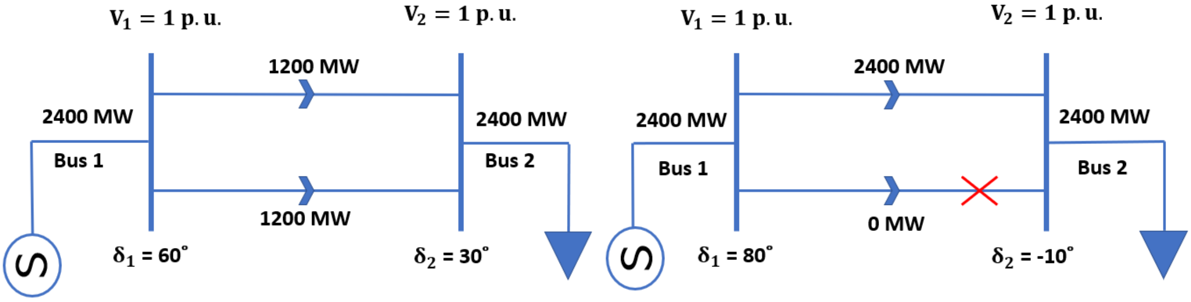


Figure 6.5: Phase angle difference changing from 30° to 90° between generation and load bus, a) before and b) after outage of line. Inspired from [65].

In the case of an outage of a line, the line can not be re-connected if the angular difference exceeds the given threshold value for the relay. Usually, the relay settings do not allow angular differences across them that exceed 40° during closure [65]. Using the angular difference, operators can then decide whether the load should be reduced to re-connect the line.

Monitoring angles may lead to increased system reliability as excessive stress can be detected. Corrective actions such as reducing load can then be implemented. Operators are also able to detect possible margins to increase loading. Thus, monitoring angles may lead to enhanced system reliability [52].

Figure 6.6 summarises relevant indicators for grid stress monitoring.

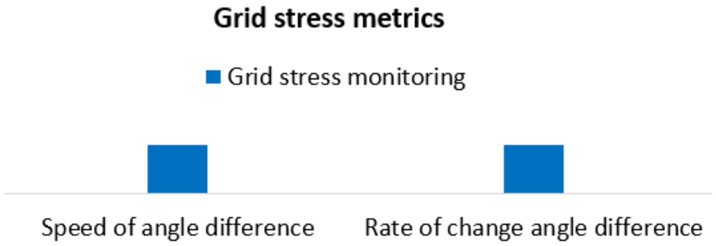


Figure 6.6: Relevant information related to grid stress monitoring.

6.5 Voltage Stability Monitoring

From Section 4.2, voltage stability relates to maintaining stable bus voltage levels, which depend on dynamic system operating conditions. The current operating point should be highlighted in relation to system constraints during real-time monitoring of voltage stability. Dynamic operating limits cause changing reliability margins, which indicate a relative amount of system load rise (MW and/or MVar) for stable operation [24]. The critical operating point for stable operation can be illustrated through PV or VQ curves, as depicted in Figure 6.7. These curves provide a relation between voltage and power levels, either active or reactive. The slope of the curve may indicate the proximity of the current operation compared to the critical point for stable operation [65]. Estimations of reliability margins must be updated during system condition changes [67].

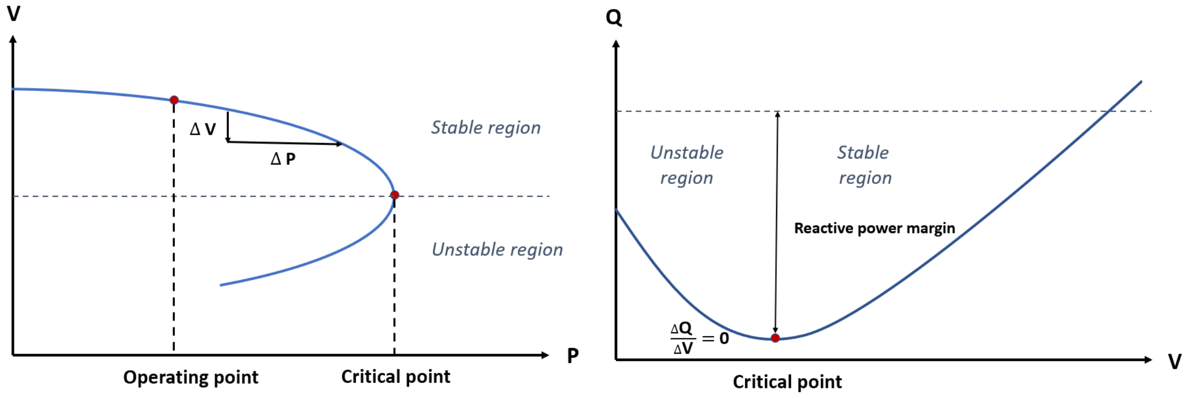


Figure 6.7: a) PV curve: voltage (V) and power (P). b) VQ curve: voltage (V) and reactive power (Q). Inspired from [68] and [69].

Traditionally, PV and VQ curves are formed through steady-state voltage analysis based on detailed system models and historical data. Implementation of PMUs, however, makes it possible to outline portions of the curve through real-time measurements. The curve will then represent a monitored critical bus or interface in the system [67].

Sensitivity analysis of voltage provides insight into the proximity between the operating point and the critical point for stable operation [58]. It may provide an early warning of deteriorating voltage conditions. *Voltage sensitivity* is defined as the ratio of the change in voltage magnitude ΔV of a bus to the change in power flowing through a line, either active ΔP or reactive ΔQ. It is, by definition, the slope of the PV/VQ curve [65]. Online assessment of voltage sensitivity can be done through linear regression [67].

Voltage sensitivity V_{sens} can be assessed for the two-bus system in Figure 6.5. The voltage sensitivity in bus 2 (based on ΔV_2) for the power flowing between bus 1 and 2 (ΔP_{12}) is given by

$$V_{sens} = \frac{\Delta V_2}{\Delta P_{12}}, \qquad \begin{cases} V_{sens} < 1 & \text{Approaches nose curve tip} \\ V_{sens} > 1 & \text{Overcompensated voltage.} \end{cases} \tag{6.1}$$

Voltage levels are closely related to reactive support, where low voltage can indicate inadequate reactive support. Inadequate reactive support can be caused by absent reactive reserves or conditions that prevent infusion. Consequently, control rooms should possess information regarding reactive margins (MVar). Appropriate reactive reserve levels differ in various parts of the grid, and a potential alarm system should be configured accordingly [58]. Limiting contingencies should also be presented [70]. Figure 6.8 summarises relevant information for voltage stability monitoring.

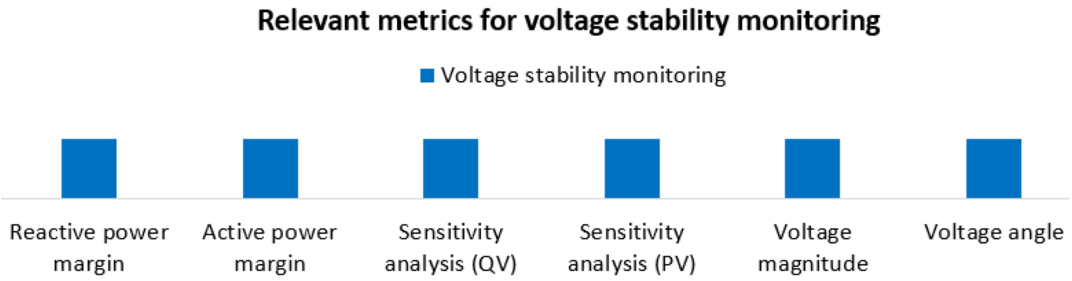


Figure 6.8: Relevant information related to voltage monitoring and trending.

6.6 Voltage and Frequency Control

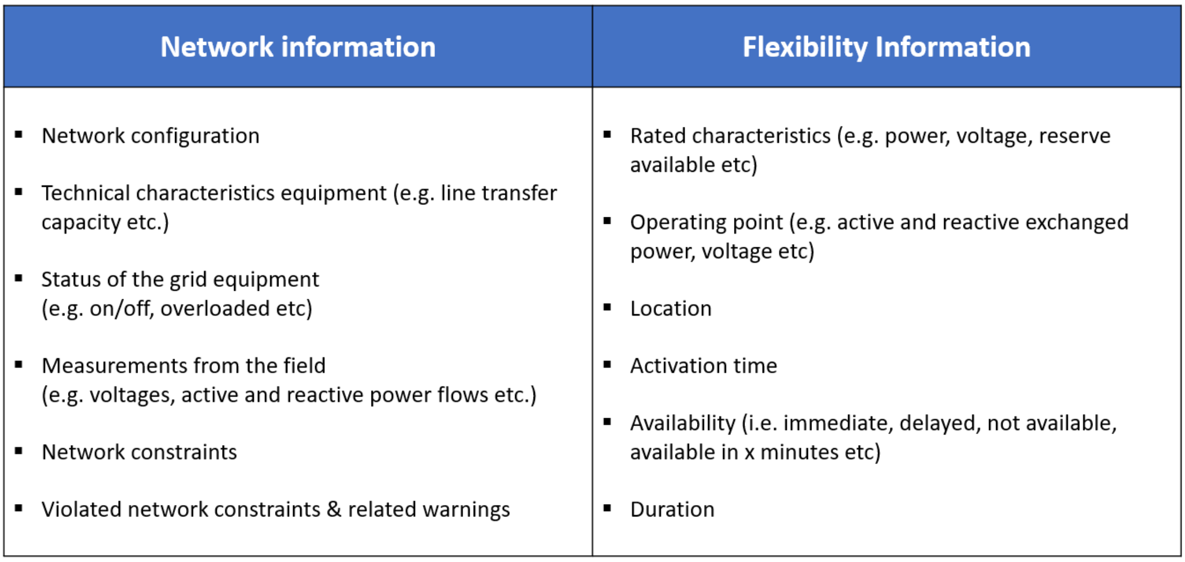
The European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids (ELECTRA) proposes future control measures for a cell-based concept. ELECTRA defines a cell as [33, p. 8]:

> *"Grid units, that each are responsible for local balancing and voltage control and consist of interconnected loads, distributed energy resources and storage units within well-defined electrical boundaries corresponding to a physical portion of the grid and corresponding to a delimited geographical area".*

The control measures include voltage and frequency. Voltage control is divided into two main pillars, whereas frequency control is divided into four. *Primary voltage control* handles restoration of set voltage point values through active or reactive power injections. *Post primary voltage control* reintroduces bus voltages back to nominal values. Additionally, this control level optimises reactive power flows to reduce network losses.

Regarding frequency control, the *inertia steering control* attempts to limit ROCOF to a maximum allowed value. *Frequency containment control* stabilises the frequency to a

Table 6.3: Network and Flexibility information defined by The European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids (ELECTRA) [71].



Network information	Flexibility Information
▪ Network configuration ▪ Technical characteristics equipment (e.g. line transfer capacity etc.) ▪ Status of the grid equipment (e.g. on/off, overloaded etc) ▪ Measurements from the field (e.g. voltages, active and reactive power flows etc.) ▪ Network constraints ▪ Violated network constraints & related warnings	▪ Rated characteristics (e.g. power, voltage, reserve available etc) ▪ Operating point (e.g. active and reactive exchanged power, voltage etc) ▪ Location ▪ Activation time ▪ Availability (i.e. immediate, delayed, not available, available in x minutes etc) ▪ Duration

set safe band. Afterwards, restoration of balance and scheduled load flows are secured through *balance restoration control*. The last step is *balance steering control*, where operators are freeing balance restoration reserves from the current cell. This layer of control uses pro-active measures based on short-term forecasts to prevent activation of frequency containment and restoration reserves [71]. Figure 6.9 presents a selection of observables related to the different stages of control for voltage and frequency. The terms “network information” and “network flexibility” are presented in Table 6.3.

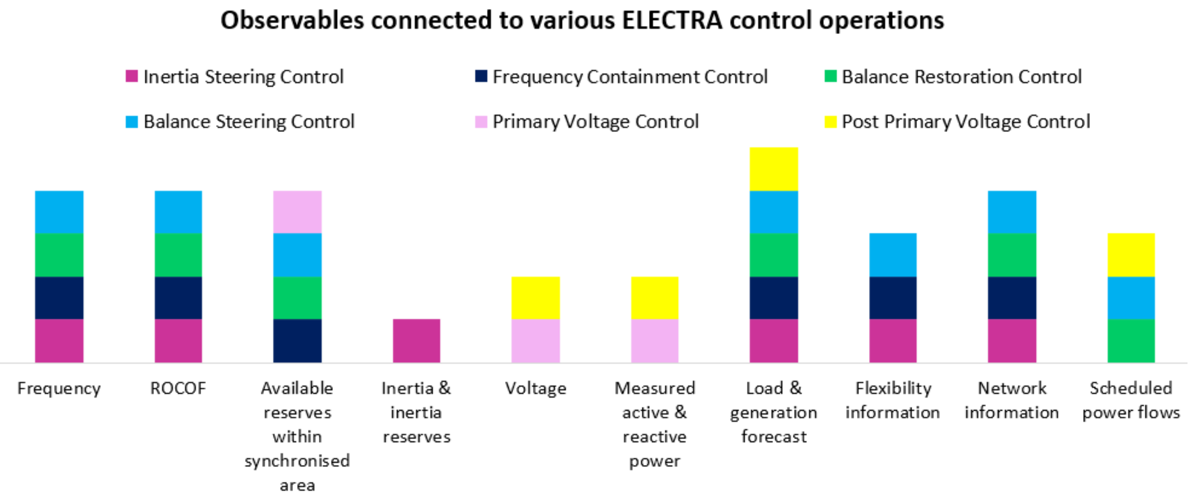


Figure 6.9: Metrics for ELECTRA voltage and frequency control operation [71].

6.7 Field Asset Monitoring

Implementation of PMUs enhances grid transparency through measurement data. However, the condition of various field assets also affects system operation. Modern sensor technology facilitates enhanced information flow of the configuration and/or real-time condition of these. Field assets not properly functioning may alter stable operation. Currently, operators monitor and control field assets offline, assisted remotely by field crews. Potentially hazardous conditions can be communicated and detected through sensors. For example, sensors can monitor the internal discharge activity in a current transformer. In turn, this could reveal conditions that may lead to explosions or fire [72]. Consequently, remote online inspection of field assets may prevent potentially dangerous affairs concerning both field crews and system operation [73].

Several system decisions can be made based on data, which can be obtained from advanced sensors and applications. Future implementation of such sensors can contribute to the following processes [51]:

- **Topology:** Map and update system topology
- **Asset status:** Determine asset status
- **State estimation:** Support improved state estimation
- **Control:** More complex real-time controls.

Physical grid components and equipment often operate within specified static constraints. These constraints commonly span the maximum range of conditions that the grid can be operated in. Such a condition could be the ambient environment temperature. Thus, conservative operation may cause underutilised capacity. These operating margins can be reduced by addressing the dynamic nature of field assets to support crucial operation situations or contingency situations. Additionally, sensors enable the transition from time-based to condition-based maintenance.

Various sensor technology related to substations, underground and overhead lines is attached in appendix C. Some overall themes for inspections are set out in Figure 6.10.

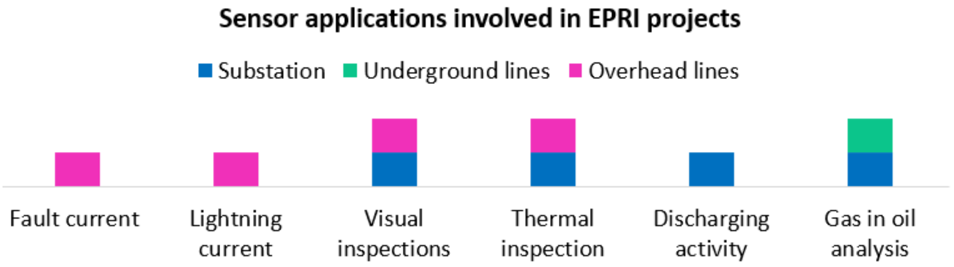


Figure 6.10: Overall sensor applications conducted in projects at EPRI. [72].

6.8 Discussion

The various metrics presented in this chapter are not necessarily final, as additional parameters may prove beneficial in the future. Nor are they completely independent of each other, as an event can trigger multiple conditions. New detection methods of instability could influence future data needs (e.g., new sensitivity assessments), which could require presently unexplored combinations of PMU data, SCADA data or other sensor measurements. However, the listed metrics provide an overview of the parameters needed for future power system monitoring applications. Additionally, the high resolution of PMU data ensures that the parameters provide enhanced transparency of the grid, compared to current SCADA solutions, when a sufficient number is mounted.

There appears to be a relatively large gap between future data needs and the present control room situation presented by the interviewee in Section 5.1. As of now, detection of islanding, oscillations and voltage instability is done with the help of an experienced eye. Such detection does not necessarily guarantee that the operator perceives the overall scope of the situation. Nor is it given how long it takes to detect arising events. Therefore, the parameters presented in section 6.2, 6.3 and 6.5 appear as clear and direct solutions to increase the situational awareness in the control room of the future.

The power grid is expected to enable The European Green Deal. However, parts of the grid are of relatively high age. Significant investments are forecast in the network infrastructure, according to [51]. Nevertheless, reconstructions are not necessarily rapid enough to keep up with the pace of increasing electricity needs. Thus, it is advantageous with solutions that forestall the development need. Precise monitoring and measures may aid the forestalling of new capacity. Hence, control room operation utilising sensor technology can enhance situational awareness and improve the utilisation of current infrastructure. This can, in turn, provide TSOs more time to develop sustainable grid solutions.

ENTSO-E has stated that successful decarbonisation depends on minimising the cost of transforming the power sector (Section 2.3). As grid equipment is expensive, it is advantageous with solutions that limit the need for new capacity. Thus, it is essential to utilise resources as optimally as possible. Through enhanced monitoring, the operating point can be adjusted to optimal exploitation of system resources (e.g. through monitoring grid stress, voltage stability and line ratings). Optimal operation still depends on the dynamic nature of the grid. From [72], advantages from sensor technology is considered high within this field, and can in some instances justify sensor investments.

From Section 2.3, future cooperation in the Nordic countries and Europe will lead to greater power transfers across large geographical areas. Cross-border cooperation presents opportunities within resource distribution and exploitation. Increased distributed generation may lead to several islanding events, according to [54]. From [74], the increasing connectivity of wind makes the system more prone to dangerous oscillations. Additionally, large inter-area power transfers may expose the system to increased system stress. Thus, it seems essential to closely monitor these conditions in the future. Future power system monitoring has to occur across national borders. Luckily, synchrophasor data enables monitoring across large geographical areas. Such insight will prove beneficial to maintain rapid insight into varying power production caused by RES. Thus, control room personnel can obtain a greater overview and adapt to intra-hour changes.

The advantage of high-resolution data is also considered a challenge. PMU data is characterised by the rapid production of large quantities of information. Hence, it can be considered as big data. Such data demands system tool solutions for both storage and handling, according to [51]. Additionally, the detailed information of critical infrastructure may appear lucrative for cyber attackers. Therefore, the implementation must be characterised by well-thought-out cybersecurity.

The ELECTRA web-of-cells concept is an example of a possible future grid structure. Cell operation unites functions across DSOs and TSOs, resulting in higher information flow and collaboration. Similarly, a combination of maintenance and control room operation is possible. Presently, maintenance and real-time operation are “separate” divisions at Statnett. However, future operation depends on a holistic grid view which may benefit from merging the two. Global climate change brings with it predictions of more extreme weather. Hence, ambient conditions can pose an increasing threat. This may lead to a greater need for field asset and weather monitoring, and monitoring the probability of equipment failure, within the control room.

From Section 1.2, it was stated that NEWEPS focuses on voltage stability, frequency stability and damping of electromechanical oscillations. Regarding voltage stability, the high resolution of PMU data is said to enable voltage sensitivity assessments. This metric has the potential to increase awareness about the proximity to instability and reflect system topology changes [65]. From Section 4.2, voltage instability can be caused by a gradual load increase. It is not given that an operator notices such gradual changes. Thus, voltage sensitivity and reliability margins seem to be powerful tools to communicate and follow the evolution more closely.

Electromechanical oscillations are considered possible to detect and locate (see Section 6.3). Detection of oscillatory activity appears to benefit from the knowledge of oscillation amplitude, damping and mode frequency. Furthermore, high-resolution data of angular differences and power exchanges can ease the localisation of the oscillatory mode.

However, it is stated that forced oscillations can be somewhat challenging to distinct from marginally stable natural oscillations. As corrective measures related to the two differ, it is essential to draw more attention to their distinctions. For example, forced oscillations demand personnel to disable its input. In contrast, natural oscillations could be damped through adjustment of load-changers or re-dispatching of generators [75]. Consequently, misconceptions of which oscillations one deals with could delay correct remedial measures.

Presented data needs in this chapter have extended beyond the focus of NEWEPS, as the literature scoping review indicates additional needs. For example, it appears beneficial to monitor grid stress through phase angle differences and field assets through sensors. Unintentional islanding has also been further reviewed. The interviewee in Section 5.1 stated that islanding is often detected relatively quickly. However, the forecast of several islanding events (from [54]) can change this trend. Highlighting clear indicators of islanding events could aid communication and detection and equip the control room for an increase in the number of islanding events. Another side of the topic relates to field crew safety, as enhanced insight into the island would optimise risk understanding. This could, in turn, also secure equipment exposed to frequency and voltage deviations.

WP2 in NEWEPS targets methods for visualisation of power system states in the control centre. The mentioned data in this chapter can be used to develop early warning signals and illustrate system details. The overall system state is a collection of all system parameters. Thus, the proposed future data needs should be able to enhance the transparency of the grid state. As the proposed data needs are “signatures” of system states, they could also be used in advanced machine learning models to predict the probable development in the near future. Furthermore, it will be necessary to focus on proposed control actions and their impact on stability margins.

7. Relevant Visualisation Methods

7.1 Visualisation tools

In 2012 the North American Synchrophasor Initiative (NASPI) organised a workshop involving 20 operators from various reliability coordinator organisations and balancing authorities in America. The goal of the workshop was to identify valuable feedback on various phasor data visualisation software programs. As the second research question of this master's thesis addresses how data should be visualised, the feedback is included.

Assessments of use case representations from various vendors were made based on visualisation and situational awareness aspects. Various events, visualised in different programs, were presented to the operators. Feedback was given based on the clarity, effectiveness and intuitiveness of the different displays. Since 2012, several of the programs have been further developed. However, the following points may still provide important reflection aspects. Further details of the workshop and software programs can be found in [76]. The following categories represent some of the most frequently occurring feedback.

Data display format: Large tables were found to be less desirable than dynamic graphs and maps. Tables were assessed as more helpful for operation support engineers than control room operators. Ease of interpretation can be strengthened through clear relations between data and information.

Dashboard: The overview display should capture global relations. The view should indicate where to look next. This implies a limited amount of details in the overview display. Geographic overviews provide a useful underlying geographical reference for the operators. Operators reported the feeling of easily getting lost when switching back and forth between different displays.

Accessing more detail: Several operators indicated "mouse-over" options could be more favourable than pop-up windows. An excessive amount of scrolling and number of windows may alter the user's navigation ability in the information space. It would be favourable for the operator to glance over different screens presenting various monitoring aspects.

Colour effect: Several operators emphasised a preference for dark backgrounds on displays. Text highlighting could be challenging with, for example, black text on a red background. Graph lines were preferably highlighted when the mouse hovered or clicked on the corresponding label.

Alarms: Alarms should contain a steady amount of information to reduce the need for further searches. Flashing alarms could alter the operator's focus and should be used with caution. The number of colours or objects in one screen should be limited and focus on information extraction. Data overload is not desirable.

Icons: Icons and symbols should resemble the object they represent. Icons can be static or dynamic. Rotating angles were, by some, highlighted as a distracting factor.

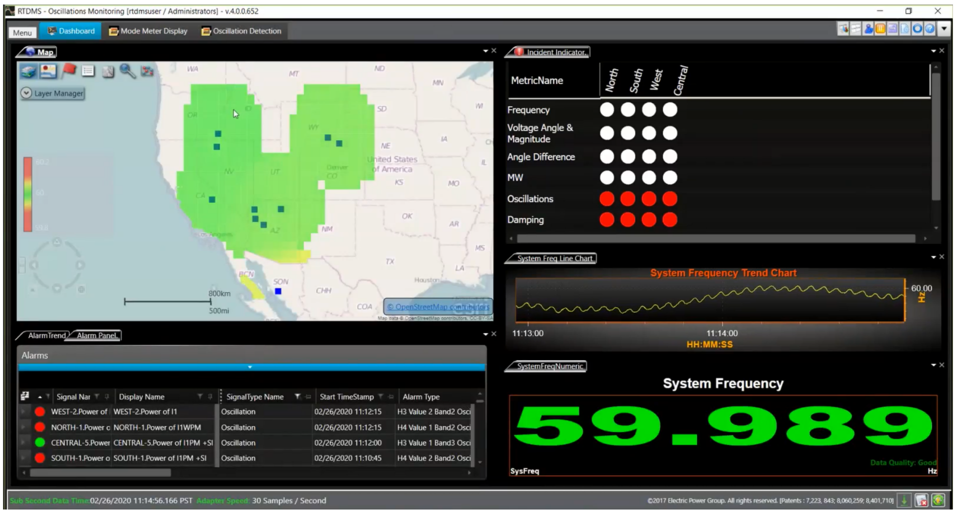
7.2 Real Time Dynamics Monitoring System

The Electric Power Group (EPG) has developed the Real Time Dynamics Monitoring System (RTDMS). Phasor data can be monitored and visualised through the software [52]. Both the Southern California Edison (SCE) and the Electric Reliability Council of Texas (ERCOT) plan for their operators to use the system in the future [77]. Various synchrophasor applications available in RTDMS are presented below [78]:

- Phase angle and grid stress monitoring
- Voltage and angle stability analysis and monitoring
- Frequency stability monitoring
- Oscillation detection
- Islanding detection.

Crucial system reliability metrics are presented to users through a range of displays. The main situational awareness dashboard illustrates an entire interconnection. It is complemented with phase angle separation of central angle pairs in the system. Arrows indicate the angle separation to given threshold values through colour coding, ranging from green to red. Green implicate operation within given threshold values. During abnormalities, the severity of potential deviations determines whether a metric is yellow or red. Additionally, various alarms are presented in a panel on the side of the interconnection. This panel includes several monitored metrics such as frequency, phase angles, voltage measurements, flows and damping, as well as the jurisdictional areas that are being monitored [52].

One of the applications of RTDMS is oscillation monitoring. The presented metrics enable operators to classify the type and severity of the oscillation. In this way, operators can identify local and wide-area oscillations as well as magnitude, damping and contributing components. Figure 7.1 presents a geographical frequency heat map at the top left corner. Frequency close to 60 Hz, the nominal value in the U.S., is presented in green. Deviations change the colour. In the figure, some areas are slightly yellow as they are affected by the oscillations in the system [79].

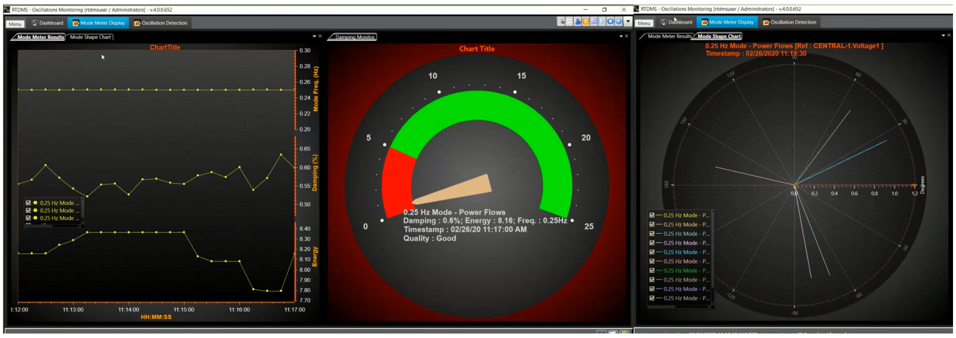


	Signal Nar	Display Name	SignalType Name	Start TimeStamp	Alarm Type
●	WEST-2.Power of	WEST-2.Power of I1	Oscillation	02/26/2020 11:12:15	H3 Value 2 Band2 Osci
●	NORTH-1.Power o	NORTH-1.Power of I1WPM	Oscillation	02/26/2020 11:12:15	H4 Value 1 Band2 Osci
●	CENTRAL-5.Power	CENTRAL-5.Power of I1PM +SI	Oscillation	02/26/2020 11:12:00	H3 Value 1 Band3 Osci
●	SOUTH-1.Power o	SOUTH-1.Power of I1PM +SI	Oscillation	02/26/2020 11:10:45	H4 Value 2 Band2 Osci

Sub Second Data Time:02/26/2020 11:14:56.166 PST Adapter Speed: 30 Samples / Second

Figure 7.1: Real Time Dynamics Monitoring System (RTDMS) dashboard for oscillation monitoring [79]. Courtesy of Horacio Silva-Saravia.

Operators can become aware of abnormalities linked to oscillations and damping through the upper right corner of Figure 7.1. The severity of the oscillations can be further reviewed in the mode meter in Figure 7.2. Mode frequency, percentage damping and energy are reported in the box on the left. The box illustrates that damping (middle plot) is decreasing and the energy (bottom plot) increasing. The speedometer-like display in the middle box illustrates the percentage damping. As the damping is below the threshold of 5 %, the display is highlighted in red. In the box on the far right, a mode shape chart is presented containing voltage amplitude, and phase relations between different generating locations in the system [79].



0.25 Hz Mode - Power Flows
Damping : 0.6%; Energy : 8.16; Freq. : 0.25Hz
Timestamp : 02/26/20 11:17:00 AM
Quality : Good

Figure 7.2: Mode meter in RTDMS [79]. Courtesy of Horacio Silva-Saravia.

Figure 7.3 illustrates the oscillation detection tab. PMUs reveal the location and distribution of the oscillations. The box on the left provides a geographical view of the location of the metrics. Four bands are presented based on predefined frequency intervals. Here, a corresponding band is coloured red at various locations- confirming that several locations are affected by the oscillations. Oscillation energy can be presented as voltage magnitude (VM), MVar or MW in the upper right display. Band 2, the red section in the geographic view, is above the energy threshold in the oscillation detection trend chart. It represents the inter-area oscillatory mode [79].

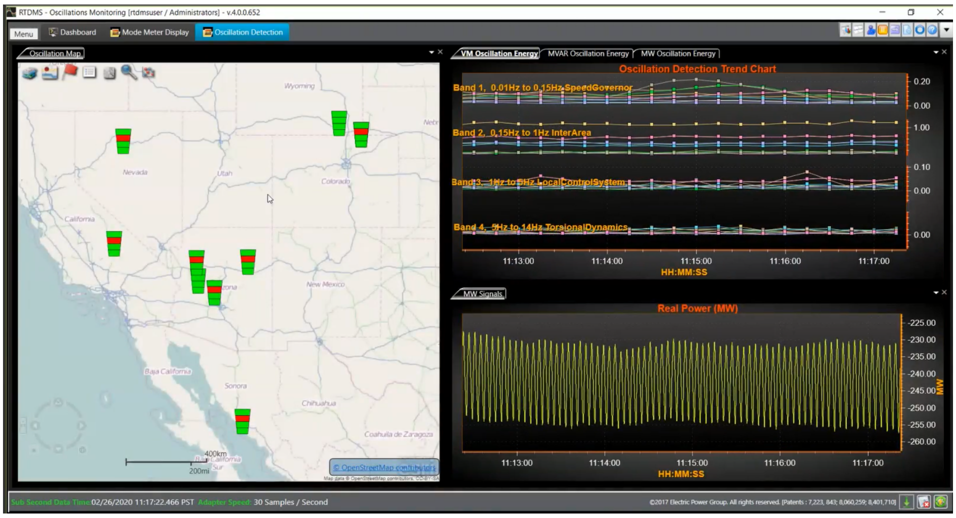


Figure 7.3: Real Time Dynamics Monitoring System (RTDMS) oscillation detection display. Retrieved from [79]. Courtesy of Horacio Silva-Saravia.

Another application of the RTDMS is islanding detection and re-synchronisation. According to EPG two factors act as clear indicators of an islanding event: frequency separation and rotating voltage angles. These can be detected by PMUs. From Figure 7.4 the frequency and voltage of both sides of an island are presented. The display at the upper left corner visualises the frequency separation, whereas the numeric values are presented below. Rotating voltage angles are presented in the middle window. This window also specifies an appropriate range for re-synchronisation, highlighted in green shading. The different voltage levels are presented to the right [78].

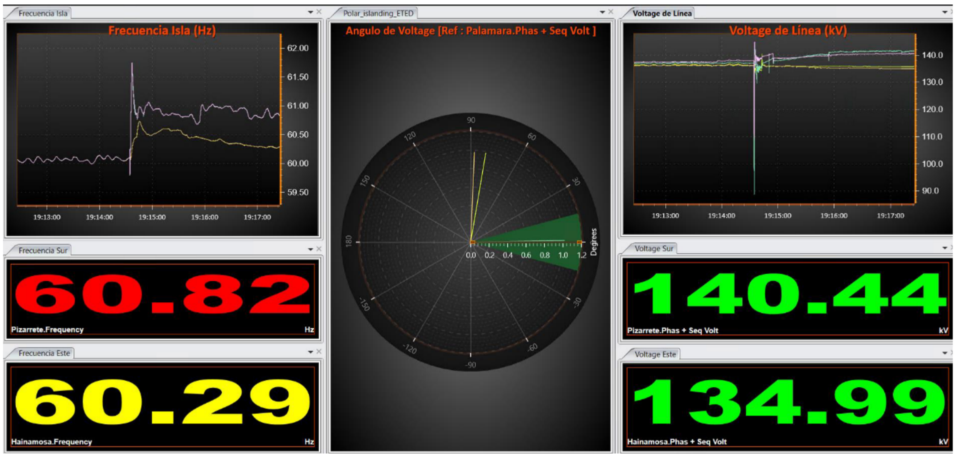


Figure 7.4: Islanding detection and monitoring in Real Time Dynamics Monitoring System (RTDMS). Retrieved from [78]. Courtesy of Horacio Silva-Saravia.

7.3 Augmented Virtuality

Remote inspection of power system substations can provide information about field assets. Thus, operators with access to remote inspection systems may rapidly inspect components during failures. Prompt remote inspections can enhance system reestablishment routines and speed up failure diagnostics [80]. Such an implementation can reduce the need for manned stations. As power systems are considered critical infrastructure, it may be desirable to combine information channels. Therefore, it can be beneficial to implement equipment such as cameras, drones and microphones at various sites.

Usage of Augmented Virtuality (AV) can be a solution for remote inspections. Augmented virtuality facilitates a combination of both real and virtual aspects during visualisation. The system can interact with real data provided by SCADA. Such operation facilitates rapid visual remote inspections and detection of inconsistencies. The following example is based on [80].

Three-dimensional models of sites such as power substations can be created based on construction drawings. Field images may then be implemented through techniques that overlap the field image with the virtual representation. This technique is named “2D-3D spatial image registration”. Field images provide 2D information, whereas the virtual representation is in 3D. Various camera sensors are related to specific field assets. Field assets could be circuit breakers, transformers or power switches. The substation collects both images and sensory data and forwards it to remote control rooms. If these sources provide conflicting states, an alarm is triggered.

Both analogue values, such as the voltage of a transformer and device states, are monitored through SCADA. Device states could be an “open” or “closed” asset. An example of such a field asset is a disconnector switch, which will be reviewed in augmented virtuality below.

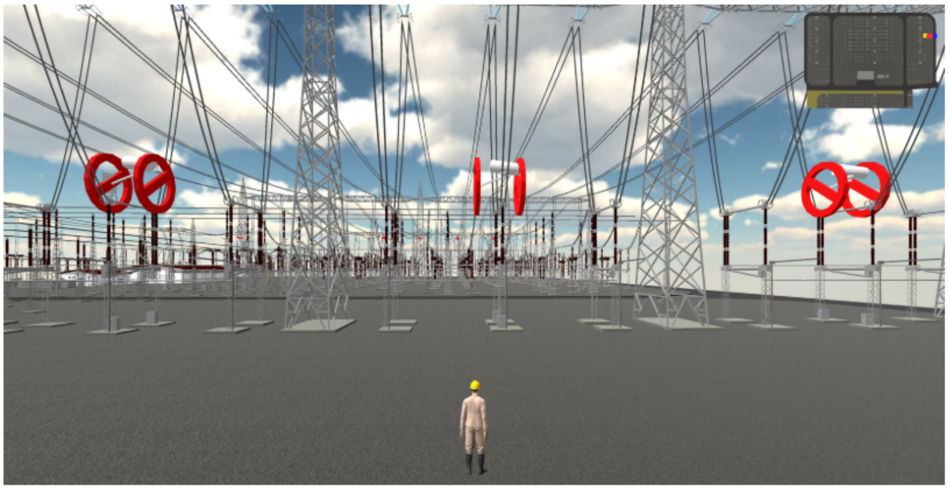
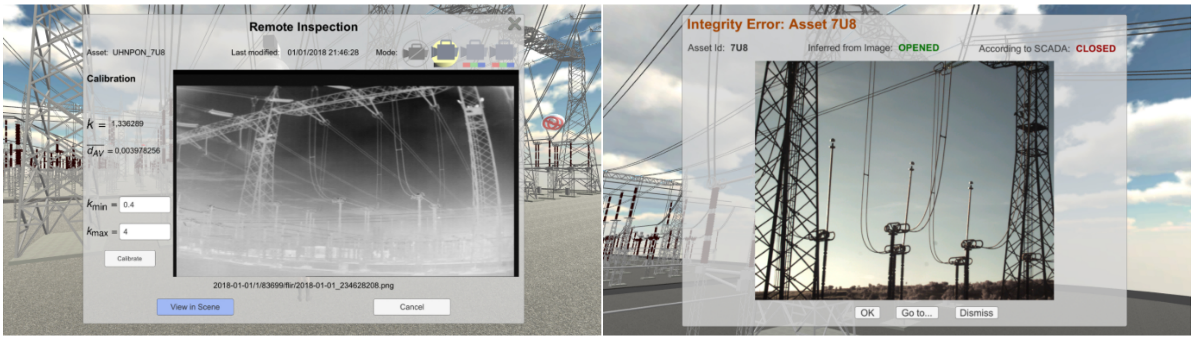


Figure 7.5: Three-dimensional representation of a substation. All cameras are disabled in the initial state [80]. Courtesy of Leandro Mattioli.

Figure 7.5 illustrates a visualisation of the initial state of a substation where all cameras are disabled. Red markers appear above monitored assets in the virtual representation. The red markers are interactive and allow users to open a configuration dialogue. The configuration dialogue in Figure 7.6 enables users to select camera views. Additionally, it provides metadata such as the time for the last modification. Camera views could, for example, be given as thermal or red, green and blue (RGB).



Remote Inspection

Asset: UHNPON_7U8

Last modified: 01/01/2018 21:46:28

Calibration

k = 1,336289

$\overline{d_{AV}}$ = 0,003978256

k_{min} = 0.4

k_{max} = 4

2018-01-01/1/83699/flir/2018-01-01_234628208.png

Integrity Error: Asset 7U8

Asset Id: 7U8

Inferred from Image: OPENED

According to SCADA: CLOSED

Figure 7.6: Remote inspection of a substation. Camera options and metadata are provided [80]. Courtesy of Leandro Mattioli.

Switch state detection can be implemented through image analysis and machine learning to automatise the assessment of system conditions. As errors can occur both in the SCADA system and during image analysis, the program will present alarm dialogues during discrepancies. Figure 7.6 presents an alarm caused by such a discrepancy. Here, two different states are presented for the disconnector switch, namely "opened" and "closed". Thus, the operator can be informed in different ways about substation conditions and potential contradictions.

7.4 Digital twin

A digital twin facilitates the perception of complex systems through static and dynamic software-based modelling and simulations. The characteristics of a digital twin are that it consists of a real space as well as a virtual space. Here, the real space consists of physical products, whereas the virtual space contains virtual models. Data is gathered in the real space and forwarded to the virtual space. The virtual model then processes the data and returns information that may aid decision support in the real space [81].

Based on the information above, a digital twin consists of three main components:

1. Physical products in real space
2. Virtual models in virtual space
3. Data and information that links the product and model together.

What separates the digital twin from many digital representations is especially the connection to the real world. Big data analytics and artificial intelligence are both applicable to digital twins. Digital twins also offer the unique opportunity to explore “what if”-scenarios. This opportunity can be used in the power system to facilitate online security analysis or as an innovative training approach for control room personnel.

Kongsberg Digital is currently involved in a research and development project in collaboration with BKK Nett and Statnett, among others [82]. The project aims to develop a digital twin, namely KogniGrid. As of today, the project is not yet finished. Autumn 2020, the project resulted in its third prototype. Per now, the twin does not include input from SCADA, nor PMU. However, input from SCADA is considered desirable. The implementation is challenged by factors such as information security. Usage of pictures and videos from drones, telephones etc., have been discussed. The proof-of-concept included a 360° image presenting the inside of a network station [83].

Kongsberg Digital has previously developed Kognitwin Energy. The Kognitwin Energy platform contains elements of interest within oil and gas. The digital twin has been implemented by Norwegian Shell at Nyhamna in Norway [84]. Through a Google Earth display, the user can manoeuvre to the desired location. Figure 7.7 illustrates an unmanned oil platform. The virtual model is presented as a 3D model based on material from the platform construction. Additionally, ambient weather conditions and surrounding marine traffic are implemented in the model [85].

Users may take a deeper dive into the virtual model. Real-time data from the field, as well as physical model estimations, are available for operators. Thus, the production area can be more thoroughly investigated. Details are presented when the user tags an

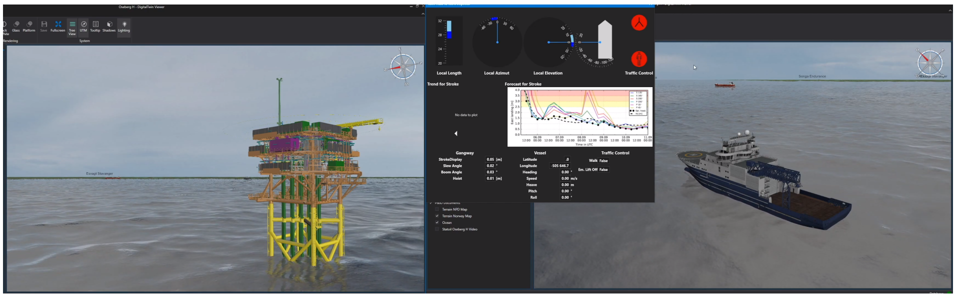
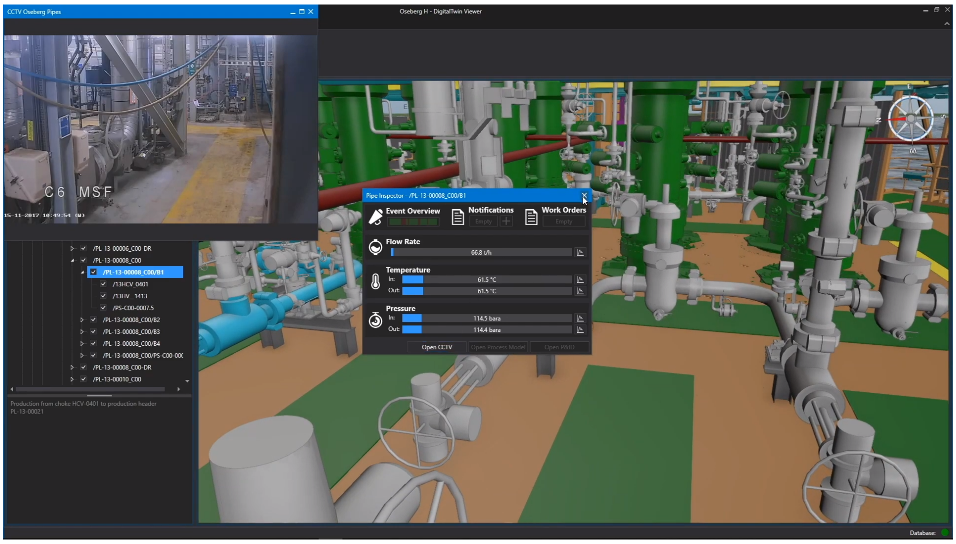


Figure 7.7: Snapshot of virtual model in Kognitwin Energy demo [85]. Courtesy of Kongsberg Digital.

object, illustrated in Figure 7.8. Examples of details include flow rates, temperatures and pressure measurements. Transmitter validation is also presented to inform about events such as drifting measurements. Information regarding severity, state and time is displayed during transmission errors. In certain cases, cameras are available at the location, which can be viewed in the virtual space.



☑ /PL-13-00006_C00-DR
☑ /PL-13-00008_C00
☑ /PL-13-00008_C00/B1
☑ /13HCV_0401
☑ /13HV__1413
☑ /PS-C00-0007.5
☑ /PL-13-00008_C00/B2
☑ /PL-13-00008_C00/B3
☑ /PL-13-00008_C00/B4
☑ /PL-13-00008_C00/PS-C00-00(
☑ /PL-13-00008_C00-DR
☑ /PL-13-00010_C00

Production from choke HCV-0401 to production header
PL-13-00021

Pipe Inspector - /PL-13-00008_C00/B1

Notifications: Empty
Work Orders: Empty

Flow Rate: 66.8 t/h

Temperature
In: 61.5 °C
Out: 61.5 °C

Pressure
In: 114.5 bara
Out: 114.4 bara

Figure 7.8: Snapshot of details presented of virtual model in Kognitwin Energy demo [85]. Courtesy of Kongsberg Digital.

Overview options can be regulated through visualisation levels. The user can filter information based on tags. In Figure 7.9 the process is visualised, and the user selects metrics from a panel. Chosen metrics are visualised through colours in the pipes in the figure on the right. This visualisation provides a quick overview and enables rapid detection of abnormalities. In this case, mass flow is illustrated. The colours visualise the degrees of production, whereas red implies maximal production. Two red triangles are presented on the right side of Figure 7.9. These represent unexpected behaviour in the relevant pipes.

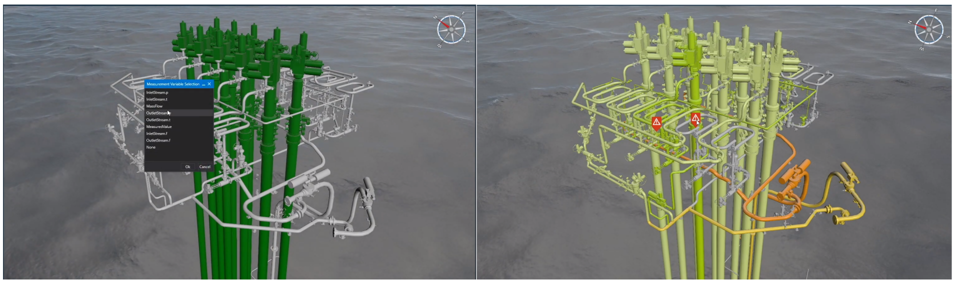


Figure 7.9: Production process in Kognitwin Energy [85].

7.5 Discussion

Findings in Section 7.1 suggest that optimal visualisation of data can be promoted through several factors. For example, it appears as if text challenges should be taken into consideration (e.g., black text on red background). Additionally, it seems favourable for graph labels or lines to be highlighted when hovered or clicked on. Consequently, the context of a given measurement can be presented clearly and ease the interpretation process. Dynamic graphs appear favourable to detect dynamic changes. Such graphs could be accessed through information quests such as “mouse-over” options. Active use of colour rendering and realistic visualisations (e.g., geographical map, substation, power plant etc.), could make the visualisation intuitive. It is important to emphasise that these findings do not necessarily represent the views of Statnett’s employees. Nevertheless, they highlight the importance of including operators in the design process.

Based on section 4.1.2 and 7.1 it appears beneficial to limit the need to switch back and forth between displays. The interviewee in Section 5.1 also requested the structure across screens to be identical. To enhance the situational awareness in the control room, it can thus be beneficial to present all visualisation aspects within the same program. Hence, an operator would not depend on several software vendors, which could result in less time spent cross-checking data across applications.

Not all currently developed visualisation projects are presented in this chapter. The presented selection is based on statements from *Gartner Top 10 Strategic Technology Trends for 2019*. Gartner describes itself as an objective research and advisory company [86]. Digital twins and immersive technologies are highlighted as promising digital technologies. Immersive technologies include augmented reality, mixed reality, and virtual reality [87]. However, the literature scoping review mainly promoted projects that focused on personnel training, control room design solutions, or nuclear radiation [88][89][90]. It was redeemed desirable to include a project that promoted a real-time visualisation concept for power grid operation. Thus, AV was selected based on its ability to provide such real-time utility value. Additionally, it combines the promising technologies augmented reality and virtual reality.

The three presented visualisation solutions differ in their degree of development. According to [77], RTDMS is presently not implemented for real-time use in control rooms. The system is explored in a test environment by ERCOT. Additionally, SCE considers RTDMS to be in a pilot form for control room usage. Consequently, the TRL seems to be around 6. Thus, the software demands further work before implementation in control rooms. The RTDMS software can be considered as the most traditional of the three represented solutions. However, the program facilitates the usage of modern PMU applications. These are highly related to the presented data in Chapter 6. Additionally, the "traditional" design may aid operators in transitioning from today's solutions.

Section 7.3 presented an example of AV substation monitoring. The mentioned project is in the process of providing experimental proof of concept for grid operation. Hence, the presented technology is assigned a low TRL. According to [80], the AV solution has been tested on a dataset consisting of timestamps and images. Additionally, a simulated SCADA subsystem was used to trigger alarm dialogues. The AV solution results in TRL 3, as it is in a research phase and includes experiments to confirm the properties of the technology. A challenge with this solution is that it is not yet combined with general PMU and SCADA parameter monitoring. Thus, it does not meet all future data monitoring needs. Consequently, the presented AV solution would only function as an additional field asset monitoring display. Furthermore, the solution is not necessarily compatible with other monitoring systems and associated procedures.

Regarding digital twins, two projects have been presented. Kognitwin Energy is implemented at Nyhamna gas processing hub. According to [84], the twin is regularly assessed and improved in its operational environment. Consequently, Kognitwin Energy has a TRL around 7-8. However, [83] indicates Kognigrid to be at a lower TRL. The project is a research and development project. Therefore, Kognigrid is assigned a TRL around 3-4. A limitation with Kognigrid, concerning data needs presented in this master's thesis, is that it will not consider PMU data. Nor has it yet implemented SCADA input. However, digital twins still enable a combination of "traditional" and field asset monitoring. Additionally, its potential for remote inspections could provide leaner communication across teams and disciplines. Hence, providing enhanced communication channels from the current use of e.g., telephone calls. There is also potential in reducing time spent on field inspections and evolving innovative training approaches.

As NEWEPS seeks concepts for visualisation, section 7.2, 7.3 and 7.4 present innovative solutions. Even though the visualisation methods are not broadly implemented in power systems, they serve great potential. Especially digital twins ability to combine elements from system parameters, weather, remote inspections and training. Thus, it can present a holistic grid view with "all" aspects taken into account and facilitate well-informed decisions. From Section 5.2, future usage of automated operation and machine learning algorithms have great growth potential. Thus, future visualisation solutions require that one can add such features continuously.

8. Case study

8.1 Power System Simulator for Engineering

System events affect network parameters in diversified ways. Voltage stability is closely related to the available transmission and generation capacity, with respect to the load demand. Thus, a change in transmission capacity can in theory alter voltage stability. The relation between transmission capacity and load demand is further reviewed in this section. To assess the interdependence, the following points were regarded:

- Evaluation of a single bus [kV]
- Gradual increase of load demand [MW]
- Transmission line connection [connected **or** disconnected].

Through the usage of the software tool PSSE and Python, one specific bus was evaluated under two distinct circumstances. The load demand was gradually increased in both cases. Three nearby transmission lines were detected as the main transmission suppliers for the chosen bus area. The line area is referred to as "Vestsnittet". By disconnecting one of these lines, it was thus possible to restrict the power supply. Hence, the nature of the bus could be investigated for two distinct grid states:

1. **Transmission line *connected:*** Evaluating the bus nature through PV curves based on the connected transmission line (base case).
2. **Transmission line *disconnected:*** Evaluating the bus nature through PV curves based on the disconnected transmission line.

Both voltage (kV) and load demand (MW) were noted during the simulations, resulting in the scatter plots in Figure 8.1. Note that the curves present the nature of the bus when subjected to the "entire" span of load demand. The PV curves are divided into the upper and stable region (orange points) and the bottom unstable region (blue points).

Each curve was defined as *lightly*, *medium* and *heavily* loaded, based on the nature of the slope in various areas (illustrated with red markings). Figure 8.1 b) operate with

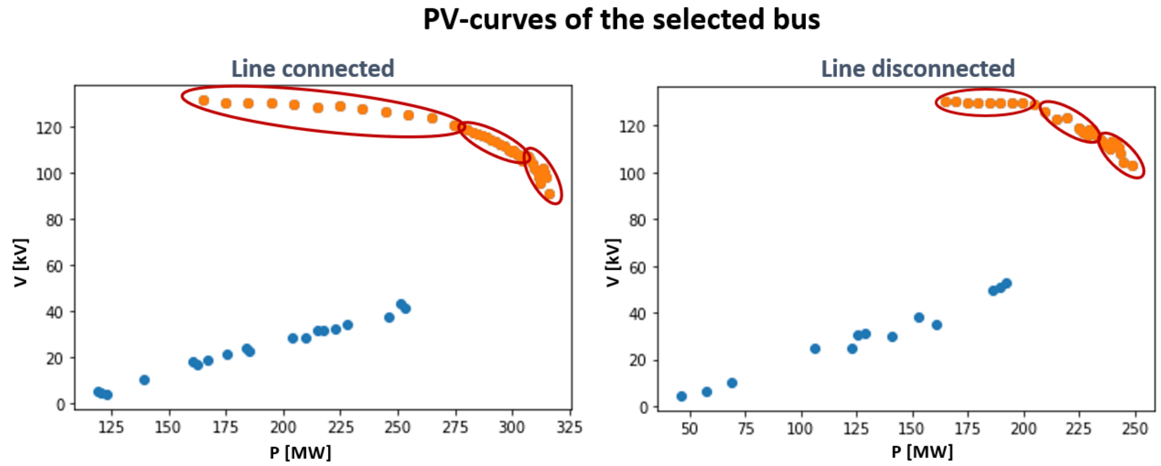


Figure 8.1: PV curves developed with line a) connected and b) disconnected .

narrower transition boundaries between load conditions than a). This is due to the fact that the curves differ in their range of power margin. From Figure 8.1 a) the critical point for stable operation is around 320 MW. In 8.1 b) it is around 250 MW. Thus, the reliability margin of the PV-curve is narrowed by around 70 MW.

Section 6.5 stated that the slope of the curve could indicate the proximity of the current operation compared to the critical point for stable operation. Hence, voltage sensitivity could be evaluated to indicate the associated risk for various load conditions. Here, the evaluation is reserved for the upper stable part of the curve of the base case. Each load condition was assessed, resulting in Figure 8.2. The slope (blue line) indicates steeper decline closer to the final stable measurement.

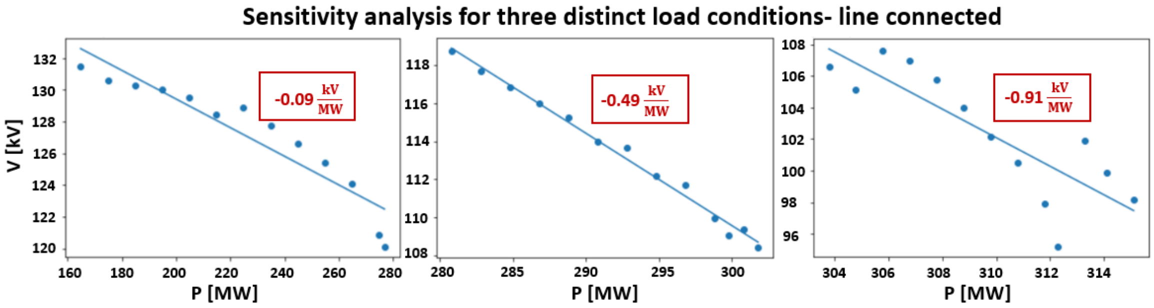


Figure 8.2: Sensitivity of bus with nearby transmission line connected for a) *lightly*, b) *medium* and c) *heavily* loaded operation.

Comparison of the sensitivity within the same load demand across 8.1 a) and b) could indicate the impact of reduced transmission capacity. Thus, Figure 8.3 depicts the corresponding load region. The data density differs within this region for the two curves. However, the overall shape of 8.3 a) suggests that this area is fairly stable so that the points can be considered representative of the slope.

The sensitivity of the bus (with the line connected and disconnected) within the common

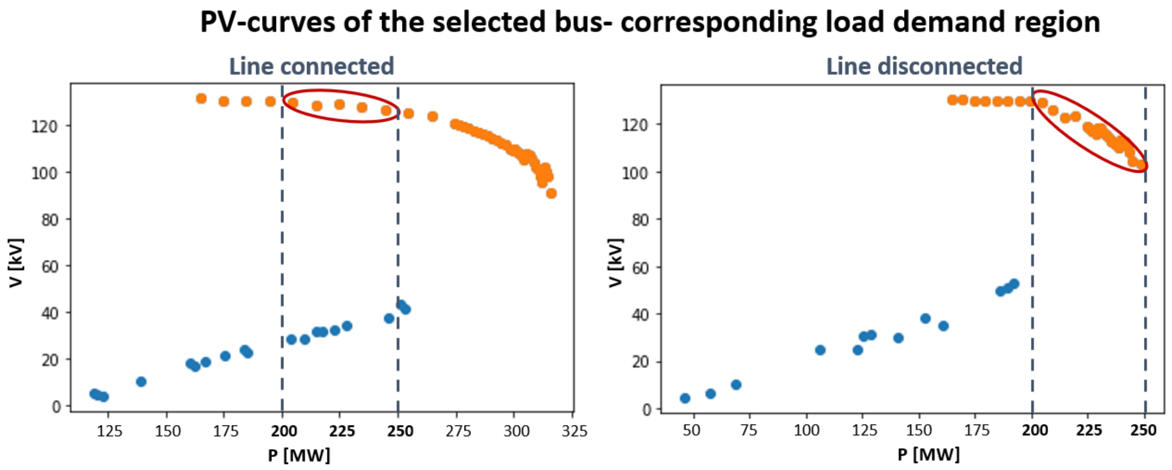


Figure 8.3: PV curves developed a) with line connected and b) with line disconnected. The region of interest is highlighted within the dotted lines.

load interval is presented in Figure 8.4. As depicted in the figure, the sensitivity is -0.066 $\frac{kV}{MW}$ and -0.49 $\frac{kV}{MW}$ for a) and b), respectively. Thus, the declination is approximately seven times steeper with the line disconnected than connected within the same interval.

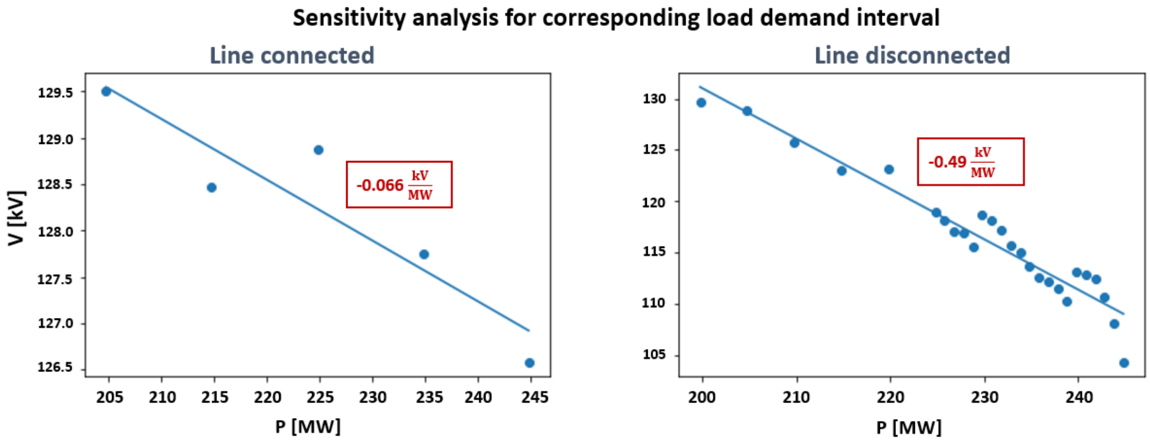


Figure 8.4: Sensitivity within area of interest with line a) connected and b) disconnected.

8.2 Discussion

As mentioned in Section 3.4, the reviewed case in Section 8.1 was dependent on the transmission capacity from “Vestsnittet”. From [20], the outage of a line is considered probable due to the risk of landslides in the geographical area. Additionally, each line has a physical limitation in terms of power transmission. Figure 8.1 depicts that the possible load demand is dependent of the available transmission of power. The interdependence is highlighted through the outage of one of the three lines in 8.1b). The tolerable load demand is clearly restrained as a result of the reduction in transmission capacity. Hence, the evaluated system is seemingly prone to transmission changes. Consequently, the *lightly* loaded region in Figure 8.1a) can not constantly be considered a safe load demand interval. This strengthens the suggested necessity of dynamic insight into reliability margins in Section 6.5.

Figure 8.2 depicts how the voltage sensitivity responds to load increases. As stated in Section 6.5, the bus is increasingly sensitive the closer the load is to the critical operating point. Furthermore, a common load demand interval was assessed for the two distinct simulations (connected **or** disconnected transmission line). The bus became approximately seven times more sensitive with the line disconnected than connected. The increased sensitivity indicates that voltage sensitivity reflects the changes applied to the system. Thus, the case study supports that voltage sensitivity is a powerful tool to assess voltage stability, as stated in Section 6.5.

During real-time operation, the operating point would represent one of several possible states on a PV-curve. An operator would depend on real-time information to assess the dynamic nature of the grid. This would facilitate continuous security assessments, which could be supported through voltage sensitivity analysis. The real-time operation would provide measurements for both voltage and power, which provides the basis for tracing out parts of the PV-curve (see Section 6.5). Hence, linear analysis and other extrapolating estimation methods could be used to define voltage sensitivity and reliability margins. The case study simulation demonstrates this concept statically. Thus, future research could include corresponding assessments of dynamic network data.

The line disconnection could pose another examination aspect. It would be interesting to monitor the trending angle difference between buses in the grid to assess system stress. This could provide the operator with an indication of topology changes and excessive loading. Additionally, as stated in Section 6.4, it is not necessarily possible to reconnect the line if the angular difference across it is too large. The operator could thus be able to reduce the load or implement other corrective measures. Thus, several indicators providing decision support for an operator could be implemented.

9. Conclusion

9.1 Conclusive Summary

This master's thesis is a part of WP2 within NEWEPS, which is about the visualisation of power system states. The examined research questions dealt with future data needs and how they should be visualised. Interviews were conducted to map state-of-the-art observability at Statnett and to emphasise the gap between current and future solutions. Literature scoping reviews were carried out to find indicators of various operational situations, how they are best visualised, and visualisation solutions that are currently being developed. Finally, a case study was conducted to test the applicability of proposed voltage stability indicators, namely voltage sensitivity and reliability margins.

From the interviews, the present operation at Statnett is shown to be based on nearly static SCADA input. It is found that SCADA has inadequate data resolution for future operation. Additionally, it lacks synchronisation of measurements. Control room personnel are found to collaborate with field crews, by telephone and e-mail. Presently, Statnett has mounted about 120 PMUs and another 60 are planned. The interviews revealed that control room personnel do not use these PMUs, partly because events happen elsewhere than the mounting locations.

The literature scoping review disclosed that PMU data enables rapid and dynamic representations of the grid state. The review findings suggest that synchrophasor data could be used to reflect the system state related to grid stress, dynamics, and reliability margins. It is also shown that PMUs provide powerful tools within oscillation detection and localisation, islanding and re-synchronisation, frequency variations and voltage instability. Associated indicators, such as angular differences, frequency, damping, and voltage sensitivity, have also been mapped and justified. These components provide research and development aspects for NEWEPS and could be used to represent the overall system state, system details and early warning signals.

The literature scoping review revealed that operational disruptions at Statnett have historically been highly related to ambient conditions, technical equipment, and field workers. Consequently, future control room operation could benefit from prompt visual inspections, personnel security, and acceleration of system reestablishment routines. From the literature scoping review, field asset monitoring appears as a potential solution. Sensor technology facilitates advanced remote inspections and collaboration, opposed to the present telephone use. To forestall the need to build new capacity in the grid, sensor technology is also found capable of facilitating optimal utilisation of grid resources and components.

Findings from the literature scoping review suggest that the best visualisation of data depends on several factors. The review indicates a preference for dynamic graphs and maps. It seems beneficial that overview displays present a limited number of details and alarms. Furthermore, it appears favourable to limit the need to switch between displays and formats. Control room operators seem to prefer dark backgrounds and "mouse-over" options to assess details. Operators should also be able to filter visualisations. In addition, the interview respondent requested an identical structure across the operator's screens.

From the literature scoping review, three visualisation projects have been presented. RTDMS has the most traditional design but utilises modern synchrophasor applications. It can be used to monitor system conditions such as islanding events, oscillations, voltage stability and grid stress. The author assigned RTDMS TRL 6, as it is not currently used for real-time control room operation. Furthermore, AV was presented as a solution for remote inspections and field asset monitoring. The presented project was assigned TRL 3. The technology fell short as it could not monitor various PMU and SCADA parameters. Digital twins were also explored. The research and development project Kognigrid was assigned TRL 3-4. The project did not aim at implementing PMU data but rather SCADA input.

Through the case study of "Sørnettet" in PSSE, both voltage sensitivity and reliability margins were examined. Load and transmission changes affected the PV curves of a selected bus. The critical point for stable operation narrowed from approximately 320 MW to 250 MW after a transmission outage. Operation within the same load-interval resulted in an increase in sensitivity from -0.066 $\frac{kV}{MW}$ to -0.49 $\frac{kV}{MW}$ with the nearby transmission line connected and disconnected, respectively. These findings indicate that the proposed metrics are useful to assess the vulnerability of the system towards voltage instability. It is also concluded from the literature scoping review that synchrophasors could be used to trace out sections of the PV curve during real-time operation.

9.2 Further Research

The NEWEPS project is currently in an early phase. Further work will be conducted within its associated work packages, including WP2. This thesis contributes as an introductory study to both data needs and visualisation of the power system state. Thus, the master's thesis has limitations when it comes to elements such as use cases and the development of a visualisation system. Potential visualisation solutions have been presented, but detailed design solutions must be reviewed further. Several areas are considered important and appropriate to conduct further research on:

- The reviewed case should be assessed further on a large scale. Further research is needed to establish its feasibility for real-time PMU data. It is also suggested to implement an assessment of grid stress.
- Future studies should take into account that visualisation solutions should be tested and evaluated by control room personnel before implementation.
- Control room personnel could be interviewed in large numbers to identify preferences and needs in visualisation design.
- Alarm system design and content should be prioritised in further work. It should be designed carefully and could seemingly benefit from reducing the number of alarms.
- Data quality requirements (e.g., latency, accuracy etc.) should be further assessed to map the technical requirements for successful utilisation of PMU data.
- Control actions and their impact on stability margins should be further assessed. Additionally, methods to predict the probable development in the near future should be reviewed.

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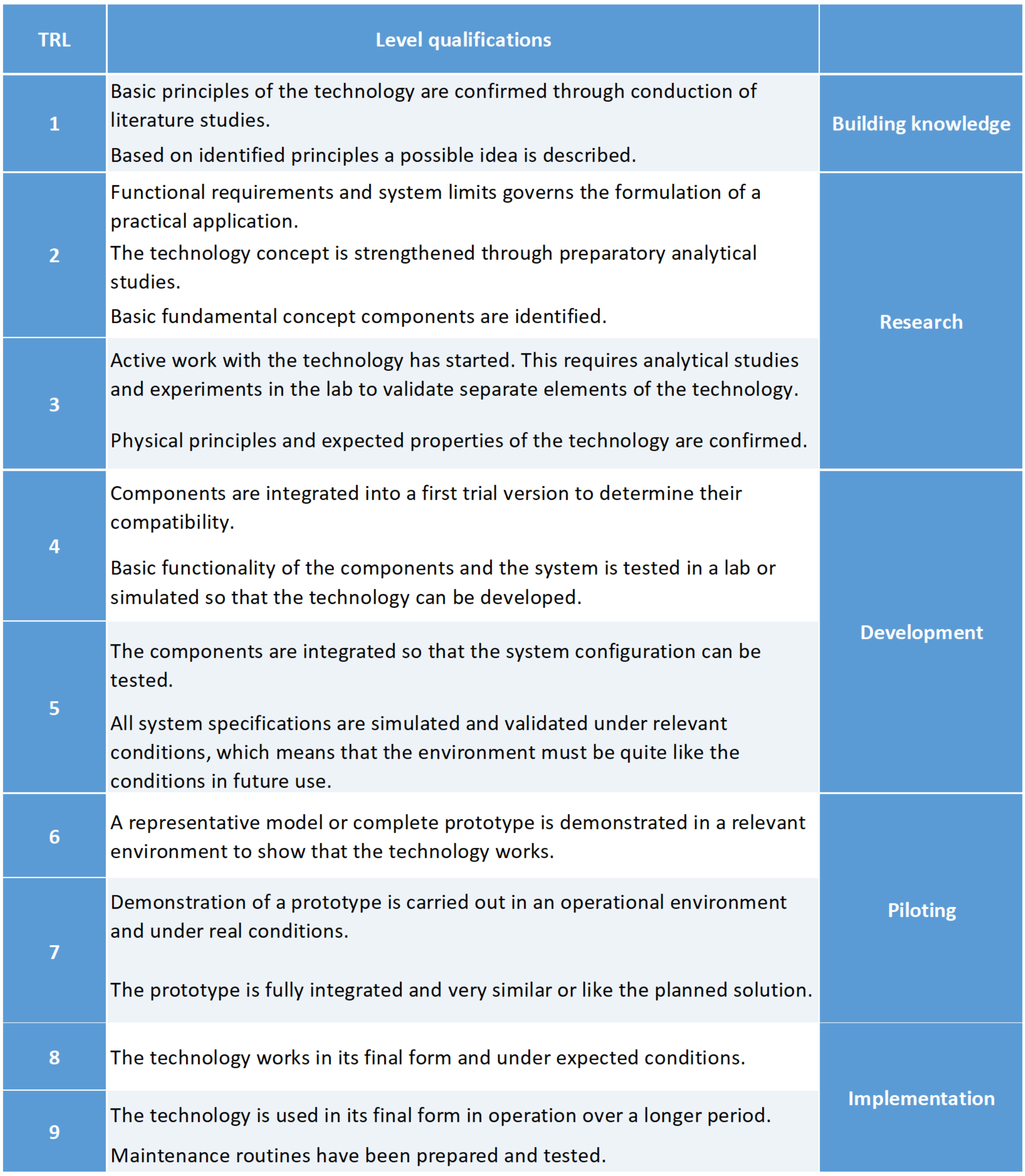
Appendix A. TRL Qualifications

Table A.1: The table contains nine TRL levels and associated qualifications. Adjusted from Statnett [91].



TRL	Level qualifications	
1	Basic principles of the technology are confirmed through conduction of literature studies. Based on identified principles a possible idea is described.	Building knowledge
2	Functional requirements and system limits governs the formulation of a practical application. The technology concept is strengthened through preparatory analytical studies. Basic fundamental concept components are identified.	Research
3	Active work with the technology has started. This requires analytical studies and experiments in the lab to validate separate elements of the technology. Physical principles and expected properties of the technology are confirmed.	
4	Components are integrated into a first trial version to determine their compatibility. Basic functionality of the components and the system is tested in a lab or simulated so that the technology can be developed.	Development
5	The components are integrated so that the system configuration can be tested. All system specifications are simulated and validated under relevant conditions, which means that the environment must be quite like the conditions in future use.	
6	A representative model or complete prototype is demonstrated in a relevant environment to show that the technology works.	Piloting
7	Demonstration of a prototype is carried out in an operational environment and under real conditions. The prototype is fully integrated and very similar or like the planned solution.	
8	The technology works in its final form and under expected conditions.	Implementation
9	The technology is used in its final form in operation over a longer period. Maintenance routines have been prepared and tested.	

Appendix B. Python Script

```python
# -*- coding: utf-8 -*-
"""
Created on Thu Apr  12 10:50:28 2021

@author: Ellen Bera Mathiesen
"""

#%% Importing all necessary packages to run the entire code

import pandas as pd
import matplotlib.pyplot as plt
import numpy as np


#%% The following section is based on the base case with the nearby transmission line connected

#%% Implementing csv file containing the dataset and defining parameters

df = pd.read_csv(’C:/Users/admin/Documents/MF-30/CASE/Endelig kode/Collected.csv’, header = None, sep = ’;’)

columnname = [’V_b [kV]’, ’Load Power_b [MW]’, ’V [kV]’, ’Load Power [MW]’]
df.columns = columnname


Vkv = np.array(df[’V [kV]’].str.replace(’,’, ’.’))
Vkv_base = np.array(df[’V_b [kV]’].str.replace(’,’, ’.’))

Pload = np.array(df[’Load Power [MW]’].str.replace(’,’, ’.’))
Pload_base = np.array(df[’Load Power_b [MW]’].str.replace(’,’, ’.’))

#%% Defining lists for later use

```

```python
V_kv = list(Vkv)
Pload = list(Pload)

Vkv_base = list(Vkv_base)
Pload_base = list(Pload_base)

Vkvstr = []
Ploadstr = []

Vkvstr_base = []
Ploadstr_base = []


for i in range(len(Vkv)):
    Vkvstr.append(float(V_kv[i]))
    Ploadstr.append(float(Pload[i]))

for i in range(len(Vkv_base)):
    Vkvstr_base.append(float(Vkv_base[i]))
    Ploadstr_base.append(float(Pload_base[i]))

#%% Scatter plot of variables

plt.scatter(Ploadstr,Vkvstr)
plt.xlabel('P [MW]')
plt.ylabel('V [kV]')
plt.title('Nose Curve (PV)')


plt.scatter(Ploadstr_base, Vkvstr_base)
plt.xlabel('P [MW]')
plt.ylabel('V [kV]')
plt.title('Nose Curve (PV)')

#%% Defining the upper stable part of each curve

Vupper_base = []
Ploadupper_base = []

Vupper = []
Ploadupper = []

for l in range(len(Vkvstr_base)-1):
    if Vkvstr_base[l] > 60:
        Vupper_base.append(Vkvstr_base[l])
        Ploadupper_base.append(Ploadstr_base[l])

```

```
for l in range(len(Vkvstr)-1):
    if Vkvstr[l] > 60:
        Vupper.append(Vkvstr[l])
        Ploadupper.append(Ploadstr[l])

#%% Plotting the stable part

plt.scatter(Ploadupper_base,Vupper_base)
plt.xlabel(’P [MW]’)
plt.ylabel(’V [kV]’)
plt.title(’PV-Curve; base case’)


plt.scatter(Ploadupper,Vupper)
plt.xlabel(’P [MW]’)
plt.ylabel(’V [kV]’)
plt.title(’Nose Curve (PV)’)

#%% First interval of base case

plt.figure()
plt.scatter(Ploadupper_base[0:13],Vupper_base[0:13])
plt.xlabel(’P [MW]’)
plt.ylabel(’V [kV]’)

X_base = Ploadupper_base[0:13]
Y_base = Vupper_base[0:13]

Xmb_base = []

m_base, b_base = np.polyfit(X_base, Y_base, 1)


for k in range(len(X_base)):
    xm_base = X_base[k]*m_base + b_base
    Xmb_base.append(xm_base)

plt.plot(X_base, Xmb_base)

plt.xlabel(’P [MW]’)
plt.ylabel(’V [kV]’)
plt.title(’Sensitivity analysis of base case: first interval of PV-curve’)
plt.show()

print("Average sensitivity in first interval of base case: {0:0.4f}".format(m_base))
```

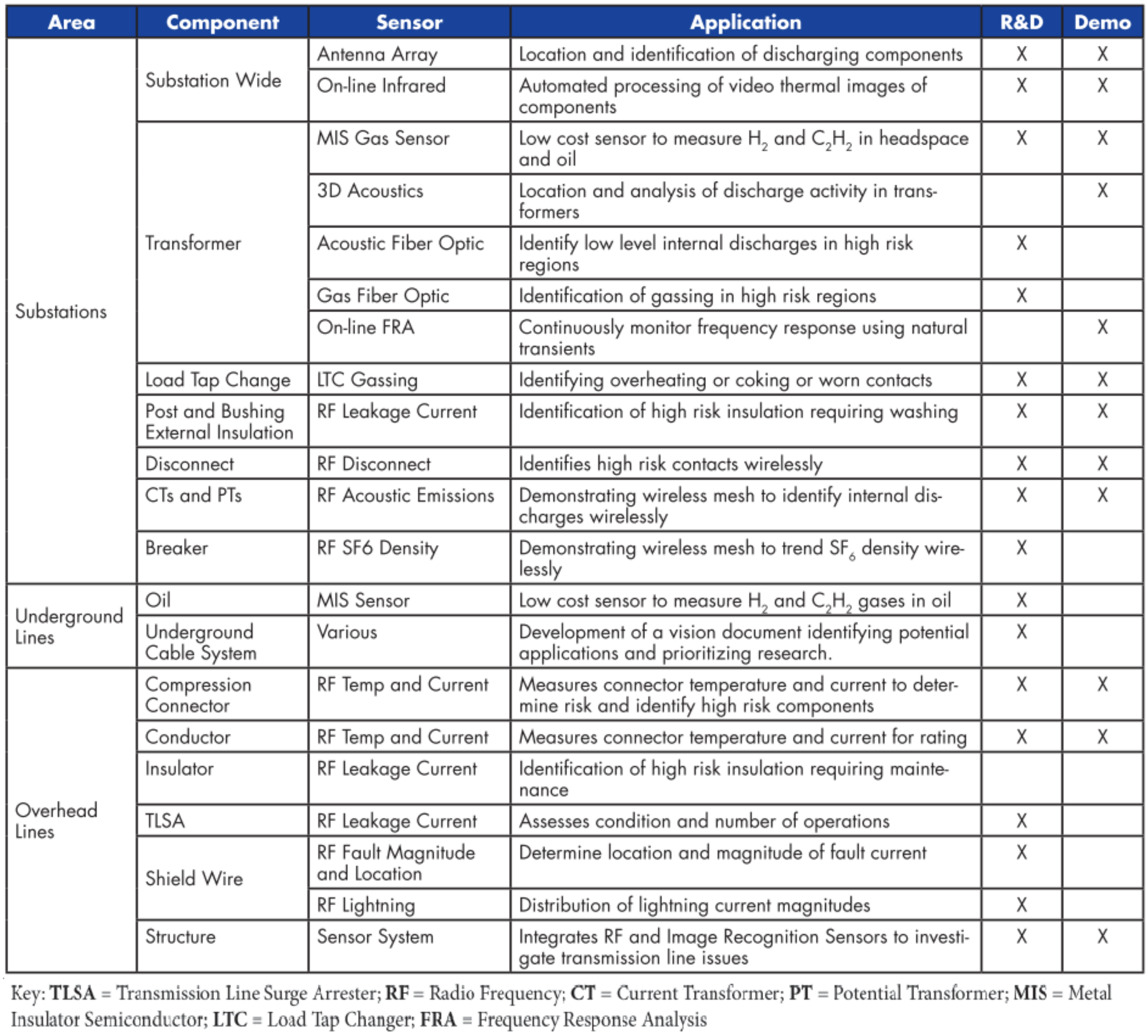
```

#%% Second interval of base case

plt.figure()
plt.scatter(Ploadupper_base[14:27],Vupper_base[14:27])
plt.xlabel('P [MW]')
plt.ylabel('V [kV]')

X1_base = Ploadupper_base[14:27]
Y1_base = Vupper_base[14:27]

Xmb1_base = []

m1_base, b1_base = np.polyfit(X1_base, Y1_base, 1)


for k in range(len(X1_base)):
    xm1_base = X1_base[k]*m1_base + b1_base
    Xmb1_base.append(xm1_base)

plt.plot(X1_base, Xmb1_base)

plt.xlabel('P [MW]')
plt.ylabel('V [kV]')
plt.title('Sensitivity analysis of base case: second interval of PV-
    curve')
plt.show()

print("Average sensitivity in second interval of base case: {0:0.4f}".
    format(m1_base))

#%% Third interval of base case

plt.figure()
plt.scatter(Ploadupper_base[28:41],Vupper_base[28:41])
plt.xlabel('P [MW]')
plt.ylabel('V [kV]')

X2_base = Ploadupper_base[28:41]
Y2_base = Vupper_base[28:41]

Xmb2_base = []

m2_base, b2_base = np.polyfit(X2_base, Y2_base, 1)


for k in range(len(X2_base)):
```

```python
    xm2_base = X2_base[k]*m2_base + b2_base
    Xmb2_base.append(xm2_base)

plt.plot(X2_base, Xmb2_base)

plt.xlabel('P [MW]')
plt.ylabel('V [kV]')
plt.title('Sensitivity analysis of base case: third interval of PV-curve')
plt.show()

print("Average sensitivity in third interval of base case: {0:0.4f}".format(m2_base))

#%% Comparison between the two distinct simulations

# Common interval; base case

plt.figure()
plt.scatter(Ploadupper_base[4:9],Vupper_base[4:9])
plt.xlabel('P [MW]')
plt.ylabel('V [kV]')

X_base = Ploadupper_base[4:9]
Y_base = Vupper_base[4:9]

Xmb_base = []

m_base, b_base = np.polyfit(X_base, Y_base, 1)


for k in range(len(X_base)):
    xm_base = X_base[k]*m_base + b_base
    Xmb_base.append(xm_base)

plt.plot(X_base, Xmb_base)

plt.xlabel('P [MW]')
plt.ylabel('V [kV]')
plt.title('Sensitivity analysis of base case; common interval')
plt.show()

print("Average sensitivity in common interval of base case: {0:0.4f}".format(m_base))



```

```
# Common interval; disconnected line

plt.figure()
plt.scatter(Ploadupper[7:33],Vupper[7:33])
plt.xlabel('P [MW]')
plt.ylabel('V [kV]')

X = Ploadupper[7:33]
Y = Vupper[7:33]

Xmb = []

m, b = np.polyfit(X, Y, 1)


for k in range(len(X)):
    xm = X[k]*m + b
    Xmb.append(xm)

plt.plot(X, Xmb)

plt.xlabel('P [MW]')
plt.ylabel('V [kV]')
plt.title('Sensitivity analysis- disconnected: first interval')
plt.show()

print("Average sensitivity in common interval of disconnected case:
    {0:0.4f}".format(m))
```

Appendix C. Field Asset Sensor Technology Table

Table C.1: The table contains information regarding sensor technologies in the power system. Adjusted from [72].



Area	Component	Sensor	Application	R&D	Demo
Substations	Substation Wide	Antenna Array	Location and identification of discharging components	X	X
		On-line Infrared	Automated processing of video thermal images of components	X	X
	Transformer	MIS Gas Sensor	Low cost sensor to measure H_2 and C_2H_2 in headspace and oil	X	X
		3D Acoustics	Location and analysis of discharge activity in transformers		X
		Acoustic Fiber Optic	Identify low level internal discharges in high risk regions	X	
		Gas Fiber Optic	Identification of gassing in high risk regions	X	
		On-line FRA	Continuously monitor frequency response using natural transients		X
	Load Tap Change	LTC Gassing	Identifying overheating or coking or worn contacts	X	X
	Post and Bushing External Insulation	RF Leakage Current	Identification of high risk insulation requiring washing	X	X
	Disconnect	RF Disconnect	Identifies high risk contacts wirelessly	X	X
	CTs and PTs	RF Acoustic Emissions	Demonstrating wireless mesh to identify internal discharges wirelessly	X	X
	Breaker	RF SF6 Density	Demonstrating wireless mesh to trend SF_6 density wirelessly	X	
Underground Lines	Oil	MIS Sensor	Low cost sensor to measure H_2 and C_2H_2 gases in oil	X	
	Underground Cable System	Various	Development of a vision document identifying potential applications and prioritizing research.	X	
Overhead Lines	Compression Connector	RF Temp and Current	Measures connector temperature and current to determine risk and identify high risk components	X	X
	Conductor	RF Temp and Current	Measures connector temperature and current for rating	X	X
	Insulator	RF Leakage Current	Identification of high risk insulation requiring maintenance		
	TLSA	RF Leakage Current	Assesses condition and number of operations	X	
	Shield Wire	RF Fault Magnitude and Location	Determine location and magnitude of fault current	X	
		RF Lightning	Distribution of lightning current magnitudes	X	
	Structure	Sensor System	Integrates RF and Image Recognition Sensors to investigate transmission line issues	X	X

Key: **TLSA** = Transmission Line Surge Arrester; **RF** = Radio Frequency; **CT** = Current Transformer; **PT** = Potential Transformer; **MIS** = Metal Insulator Semiconductor; **LTC** = Load Tap Changer; **FRA** = Frequency Response Analysis

Appendix D. Interview Guides

D.1 Interview Guide: First Interview

1. What does a normal day at the control room look like?
2. What is presented on the screens of the operators?
3. What information do you have in the control room?
4. How does the alarm system work?
5. How common is PMU input?
6. To what extent is the control room automated?
7. What kind of measurement data is of interest to the operators?
8. What should be considered when developing future control rooms?

D.2 Interview Guide: Second Interview

1. What separates the national central office from the regional centrals?
2. What is the data need of each?
3. Is AutoDIG implemented in the control rooms for real time applications?
4. How is voltage instability handled?
5. To what extent can oscillations be monitored today based on SCADA?
6. How long is the processing time before events are detected?
7. Is there adequate information about islanding events in the control room?

Appendix E. Interview Responses

E.1 First Interview

Question 1 - What does a normal day at the control room look like?

During spring season, there are around four to five operators in the regional central in the north of Norway. Overall, two needs are related to control rooms:

- Maintain an overview of the power system
- Electrical safety and handling operation.

With focus on a conductor to be reconnected, the operator is responsible for:

- Ensuring that the cable is disconnected
- Safety measures for workers on site
- The control room must ensure that the information picture is maintained during work shifts for workers on site.

Question 2 - What is presented on the screens of the operators?

An overall network image is provided on a common screen. For example, the screen in the north of Norway will show the network from Russia down to Sogndal. Typically, voltages around 66 kV are included. Voltage values of 22 kV can also be presented.

Operators usually have around seven computer screens each. Information related to the SCADA system usually occupies around four screens. Administrative information can be presented on two screens. This includes information regarding electrical safety, maintenance, contact information such as telephone numbers and e-mail. In the event of errors that reduce electrical safety, workers in the field are pulled out of the area.

Parts of the network are illustrated on screens where you can zoom in on stations for more information. Situation changes are updated every hour, but soon it is expected to be updated every 15 minutes.

Question 3 - What information do you have in the control room?

Statnett has the coordination responsibility in the power system. All licensed participators turn to Statnett as Statnett holds information of potential faults. Statnett can also request measurements from, for example, producers and power plants. These are not necessarily of the same quality as Statnett's measurements. Statnett's measurements have a time resolution given in seconds and are presented by trend curves.

The control room contains information related to the SCADA system, weather forecasts and lightning activity. Observations are also dialled in by telephone, for example if a line is down. Occasionally, an operator can have as much as 150 telephone calls within a time interval of nine hours.

Question 4 - How does the alarm system work?

The alarm system is characterised by alarms on "everything". Typically, they consist of four levels from alert to critical. For example, if a wire is removed (0 V) alarms are triggered. This leads to unnecessary alarms, which distract operators. The Peterson coil is a form of grounding in the Norwegian network. If a phase falls to the ground, you can still run the system. The situation still results in alarms. In such cases, the operators disconnect the alarm system and retrieve information using other channels.

Several alarms are linked to the SCADA system. Major errors can lead to four to five pages of alarms on the operators screens. The alarms are sorted according to importance from 1 to 4. Filtration of alarms takes place manually, based on criterias provided by the operator. Multiple events can result in seven pages of alarms. Alarm messages could be "circuit breaker switched off", "voltage-free area", "overcurrent" or "two-phase short circuit". Alarms can go on and off. It is important to sort out the important alarms.

Question 5 - How common is PMU input?

PMU input is used to a small extent in control rooms. Operators have not necessarily utilised the mounted PMUs as incidents occur elsewhere than the PMU location. The data is mainly used in research and development or for post-analysis. Utilisation of PMU data and its useful functions is a major step from the current situation. Still, there is no doubt about the usefulness of raw data and their functionality.

Control room operators can be perceived restrained or conservative towards new systems. This is due to the fact that solutions must be well developed and tested to achieve trust during operation. The operators' working days are hectic, and they do not have time to get acquainted with functionalities that do not work. Therefore, solutions must be well tested.

Question 6 - To what extent is the control room automated?

The operators recognise patterns from previous experience and applies it to current situations. They have a “clinical perspective” on the system and the knowledge sits in the “spinal cord”. It is desirable for this knowledge to be implemented in machine learning. Today, elements such as colours and numerical values are interpreted by the operators clinical view. Tomorrow’s solution to this will be digitisation and machine learning.

Many actions are remotely controlled. Examples include switching connections and values. During fault situations, human intervention is often required. During these situations, electrical safety is highly prioritised.

Question 7 - What kind of measurement data is of interest to the operators?

All SCADA measurements can be displayed as trend curves, based on second resolution. The SCADA data is somewhat dynamic, but slow. Information is lost and therefore PMU is desired, which has more frequent measurements. This will lead to high resolution trend curves. Costs have been considered as a limitation factor for implementation of PMU into the SCADA system. Nevertheless, the utility value is considered high.

Question 8 - What should be considered when developing future control rooms?

The current information flow is too extensive for the operators and must be reduced. There are many manual actions that needs to be automated. Operators are also dependent of a more dynamic system. Operation and challenges change continuously. Stable weather may cause calm operation and low maintenance needs. On the other hand, operators must also be equipped for busier operation as during extreme weather.

The structure across the operators’ screens should be identical. The structure must also be flexible and recognisable. Additionally, the old SCADA system is less prone to Information Technology (IT) security breaches. Statnett has its own fibre solutions that increase security. Here, PMU solutions are considered more vulnerable.

In Norway, traditionally local consumption is covered by local production. Disconnection have had limited consequences, as many different energy sources can be used. It is now trending towards more power driving. Here, it is desired that Norway will become Europe’s green battery, with imports and exports. This weakens the old balance, and makes security of supply more vulnerable. The system condition fluctuates to a greater extent and the operators lose track.

E.2 Second Interview

Question 1 - What separates the national central from the regional centrals?

The national central office usually operates with average values. Thus, they have limited detailed insight. The regional central on the other hand has more details about elements such as:

- Components
- Details and local knowledge
- The underlying network
- Couplings.

It is essentially the regional centrals that are the "practicing" system manager. Nevertheless, it is important to underline that operation requires collaboration.

Question 2 - Is AutoDIG implemented in the control rooms for real time applications?

AutoDIG is used by operators to sort out information as quickly as possible during operation. The program can take two minutes to present information. Such time usage can be acceptable if the operator saves time spent filtering and searching. Location of faults can be presented through AutoDIG. AutoDIG has potential to take advantage of statistics and provide the bigger picture to operators through machine learning and artificial intelligence.

Question 3 - How is voltage instability handled?

A lot of the voltage control takes place automatically. Voltage instability is often detected through observations. There are no alarms connecting the instability to e.g. the corresponding power swing. Presently, voltage stability is monitored through SCADA.

Question 4 - To what extent can oscillations be monitored today based on SCADA?

As the time resolution of measurements are restricted to seconds, this is not enough to see oscillations clearly. Operators have visually and somewhat randomly perceived oscillations through power commutations. During operation, production can be reduced to compensate for oscillations.

Question 5 - How long is the processing time before events are detected?

The time it takes to detect errors varies from situation to situation. Real time detection is preferable, but not always possible. Ground faults may take a long time to detect. When they are detected one can examine nearby work, maintenance done on the area and disconnections in relation to the fault. In the event of faulty situations, human intervention is often required, and then electrical safety is in focus.

Question 6 - Is there adequate information about islanding in the control room?

Islanding is often detected relatively quickly. Detection is usually made through operators observational ability.

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