NEWEPS

Nordic Early Warning Early Prevention System

Final Project Report
ver. 1.0

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Oppsummering

NEWEPS-prosjektet har hatt som mål å forbedre påliteligheten og effektiviteten til det nordiske kraftsystemet gjennom utvikling og implementering av WAMS (Wide Area Monitoring System) og WAMPAC (Wide Area Monitoring, Protection, and Control). WAMS- og WAMPAC-løsninger utnytter høyoppløselige og synkroniserte visermålinger av strøm og spenning fra PMU-enheter for å gi systemoperatøren et mer nøyaktig bilde av gjeldende driftstilstand og muliggjøre automatiserte vern- og kontrollapplikasjoner.

Visjon: Arkitektur, datakvalitet og visualisering

I tillegg til de konkrete delene som er utviklet i prosjektet, har en sentral del vært å belyse viktige forutsetninger og krav til et nordisk system for WAMS og WAMPAC. De arkitektoniske perspektivene fremhever behovet for en robust og integrert tilnærming til overvåking og styring av kraftsystemet, med datakvalitet som en kritisk del av WAMS og WAMPAC. Effektive visualiseringsteknikker er også en svært viktig del som muliggjør en økt situasjonsforståelse for operatører til å ta hurtige og riktige beslutninger.

NEWEPS test- og demonstrasjonsplattform

Et av hovedbidragene til prosjektet test- og demonstrasjonsplattformen som er utviklet. Denne modulære, skalerbare plattformen er designet for prototyping av funksjonaliteten til et fremtidig nordisk system for WAMS og WAMPAC, og muliggjør testing og demonstrasjon av forskjellige WAMS- og WAMPAC-applikasjoner. PMU-datastrømmene som mates til plattformen kan lastes inn fra historiske måledata, sanntidsmålinger eller fra fiktive datastrømmer generert via simuleringsprogram eller plattformens sanntidssimulator.

WAMS-applikasjoner

Applikasjoner som er utviklet fokuserer på overvåking av spenningsstabilitet, naturlige pendlinger, og forserte pendlinger i kraftsystemet. Disse applikasjonene utnytter PMU-data for å adressere detaljer rundt systemdynamikk, og forbedrer dermed operatørens situasjonsforståelse og beslutningsevne. Applikasjonene er testet og validert på ulike måter, samt integrert i test- og demonstrasjonsplattformen.

WAMPAC-applikasjoner

Applikasjoner med et tydeligere fokus på vern og kontroll er også utviklet og validert i prosjektet, samt integrert i test- og demonstrasjonsplattformen. Utviklede løsninger har som formål å opprettholde sikker og stabil drift nåt kritiske hendelser identifiseres og passende korrigerende tiltak foreslås for hvert feiltilfelle. De korrigerende tiltakene kan raskt iverksettes for å sikre stabil drift når en kritisk hendelse oppstår. Løsningene er i stor grad basert på informasjon fra PMU-målinger og bruk av optimaliseringsmetoder basert på detaljerte modeller av systemet, som er anvendelige i sanntid.

Konklusjoner og fremtidsutsikter

NEWEPS-prosjektet representerer betydelige fremskritt innen metoder som muliggjør sikker drift av det stadig mer komplekse kraftsystemet. Evalueringen av ulike WAMS- og WAMPAC-løsninger og den utviklede plattformen er et viktig grunnlag for fremtidig utvikling og implementering.

Prosjektet har demonstrert potensialet til avanserte overvåkings- og kontrollsystemer for å forbedre påliteligheten og effektiviteten til elektrisitetssystemet, og baner vei mot en mer motstandsdyktig og bærekraftig energifremtid.

Sammanfattning

NEWEPS-projektet har syftat till att förbättra tillförlitlighet och effektivitet av det nordiska kraftsystemet genom utveckling och implementering av WAMS (Wide Area Monitoring System) och WAMPAC (Wide Area Monitoring, Protection, and Control). WAMS- och WAMPAC-lösningar nyttjar högupplösta och detaljerade synkroniserade mätdata från PMUer för att ge systemoperatören en mer korrekt bild av det aktuella driftläget och möjliggöra automatiserade skydds- och kontrollapplikationer.

Vision: Arkitektur, datakvalitet och visualisering

Utöver de konkreta delar som utvecklats i projektet, har en central del varit att belysa viktiga beaktanden för att skapa bra grundförutsättningar för ett nordiskt system för WAMS och WAMPAC. De arkitektoniska perspektiven belyser behovet av ett robust och integrerat tillvägagångssätt för övervakning och styrning av kraftsystemet, med datakvalitet som en kritisk del av WAMS och WAMPAC. Även effektiva visualiseringstekniker är en mycket viktig del som möjliggör en ökad situationsmedvetenhet för operatörer att fatta snabba och korrekta beslut.

NEWEPS Test- & Demonstrationsplattform

Ett av projektets huvudbidrag är den utvecklade test- & demonstrationsplattformen. Denna modulära, skalbara plattform är framtagen för prototypframställning av funktionaliteter hos ett framtida nordiskt system för WAMS och WAMPAC, och möjliggör provning och demonstration av olika WAMS och WAMPAC applikationer. De PMU-dataströmmar som matas till plattformen kan läsas in från historiska mätvärden, mätvärden i realtid eller från fiktiva dataströmmar som genererats via simuleringsprogram eller plattformens realtidssimulator.

WAMS-applikationer

Applikationer med fokus på övervakning av spänningsstabilitet, naturliga oscillationer, samt forcerade svängningar har utvecklats inom projektet. Dessa applikationer utnyttjar PMU-data för att adressera detaljer kring systemets dynamik, vilket på så sätt förbättrar operatörens situationsmedvetenhet och beslutsförmåga. Applikationerna har på olika sätt testats och validerats, samt integrerats i test- & demonstrationsplattformen.

WAMPAC applikationer

Även applikationer med tydligare fokus på skydd och kontroll har utvecklats och validerats inom projektet, samt integrerats i test- & demonstrationsplattformen. Utvecklade lösningar syftar till att säkerställa bibehållen driftsäkerhet, där kritiska händelser identifieras och lämpliga korrigerande åtgärder föreslås för respektive felfall. De korrigerande åtgärderna kan snabbt appliceras för att säkra systemets drift ifall motsvarande felfall skulle inträffa. Lösningarna är baserade på PMU-data och använder optimeringsmetoder baserade på detaljerade modeller av systemet, som är tillämpbara i realtid.

Slutsatser och framtidsutsikter

NEWEPS-projektet representerar betydande framsteg för metoder som möjliggör en säker drift av det allt mer komplexa kraftsystemet. Utvärderingen av olika WAMS och WAMPAC lösningar och den utvecklade plattformen är en robust grund för framtida utveckling och implementering.

Projektet har visat på potentialen av avancerade övervaknings- och kontrollsystem för att förbättra elsystemets tillförlitlighet och effektivitet, vilket banar väg mot en mer motståndskraftig och hållbar energiframtid.

Executive summary

The NEWEPS (Nordic Early Warning Early Prevention System) project aim has been to enhance the reliability and efficiency of the Nordic power system through the development and implementation of Wide Area Monitoring System (WAMS) and advanced Wide Area Monitoring, Protection, and Control (WAMPAC) solutions. This comprehensive report documents the vision, methodologies, and outcomes of the project, providing a roadmap for deployment and future developments.

Vision: Architectural, Data Quality, and Visualisation Perspectives

The report outlines a vision of a Nordic WAMS and WAMPAC system, emphasizing the importance of improved assessment, coordinated assessment between Nordic Transmission System Operators (TSOs), consistent situational awareness, and enhanced state estimation. The architectural perspectives highlight the need for a robust and integrated approach to wide area monitoring and controlling of the power system.

Important considerations raised for the architectural perspectives are that:

- Coordination and pre-processing should be considered as common services to ensure fast data processing and consistency.
- When it comes to coordinated assessment, the level of autonomy may vary between different applications ranging from manually entered situational awareness information by operators to automatically issued control actions.
- Since WAMS until recently has been considered complementary in Nordic TSOs power operation, bringing the dynamic conditions into awareness should be considered with the problematic nature of digital transformations. This motivates a flexible application architecture that allows a gradual implementation and adaption of application services.
- More investigations are needed to provide guidance on whether to use a common or separate state estimator in different control systems (as SCADA/EMS and WAMS) as well as regarding if an in-house developed solution is needed to get the functionality required or if third party solutions would be the best option. However, all will introduce benefits and complexities.
- When it comes to WAMPAC, the mechanisms for assessing and managing flexible control schemes is complex. Further investigations are needed for example regarding how to model and exchange information between local and distributed applications, distributed versus different level of centralised automated control and how to benefit from AI/ML and data labelling techniques.
- TSO should have unified functional requirements, but as the maturity over time may differ in their WAN architecture the implementation may be different. A unified design supporting SDN capabilities should however be implemented in the common Nordic inter-TSO WAN network to ensure both integrity and determinism.

Data quality is a critical component of a WAMS or WAMPAC system. The report explores various methods for improving data quality, including system models and data-sharing architectures. With the large amount of time synchronised high-resolution data provided by Phasor Measurement Units (PMUs), the possibilities for advanced monitoring and control techniques are growing. However, high quality data is a prerequisite to be able to integrate such solutions into operation critical processes.

Effective visualisation techniques support the human-system collaboration, enabling operators to increase their situational awareness in order to take informed decisions in real-time. The report addresses the

increased importance of visualisation perspectives when more advanced systems, like WAMS and WAMPAC, are becoming integrated in the operation of the power system.

The report also outlines possible strategies for platform flexibility, as scalable and virtualised computing environment, portable application architecture, a flexible integration layer and the advantages with staged development using Big Data analytic and simulation capabilities.

NEWEPS Test & Demonstration Platform

A significant achievement of the project is the development of the NEWEPS Test & Demonstration platform. This platform prototypes functionalities of a future Nordic WAMS and WAMPAC system, enabling testing and demonstration of various applications, including oscillation monitoring, voltage stability, and islanding detection. The Kafka stream processing framework has been selected for integrating applications in the platform and for establishing communication between individual applications.

NEWEPS Test & Demonstration platform interface to the operator in form of a graphical user interface and to the power system in form of standard based PMU data streams originating from historians from PMUs in the Nordic grid, simulation based emulated PMU data, and laboratory based synthetic PMU data. The platform also contains functionalities for issuing alarms and visualizing information related to alarms as well as a scheme for enabling coordinated communication between neighbouring TSOs.

The platform's architecture ensures scalability, modularity, and fault tolerance, bridging the gap between research and industrial application.

WAMS Applications

The report details the development and validation of WAMS applications focused on voltage stability monitoring, natural oscillation monitoring, and forced oscillations and resonance detection. These applications leverage PMU data to provide operators with detailed and accurate information about the grid's operational situation, enhancing situational awareness and decision-making capabilities.

There are several already existing applications for voltage stability monitoring, both model-based and pure measurement based. One great benefit with measurement-based approaches is that they do not depend on state estimators nor on the knowledge of the full power system model. In NEWEPS, the voltage stability index S-Z sensitivity Indicator (SZI), which focuses on sensitivities to define whether the system is stable or not from a voltage stability perspective, has been further developed and tested. The SZI is defined using the ratio of variations of the absolute value of the apparent power of the load and the load impedance. The proposed modifications are mainly intended to improve the SZI performance in relation to network reconfiguration events and operation of regulating devices.

There are also various methods available for detecting natural oscillations using measurement data. In NEWEPS, further development and testing of the stochastic subspace identification (SSI) method have been performed. The SSI method is selected due to its ease of implementation, numerical stability, and ability to work with ambient (non-disturbance) data. The developments include how to consider the observability of modes and to cluster these based on patterns. The clustering supports the ability to track the most important oscillations over time, thus enabling preventive measures to be implemented.

Since the algorithms for detecting oscillations (system modes) using PMU measurements are generally not designed to operate in the presence of forced oscillations, they risk giving biased results if a force oscillation is present. It is therefore important the WAMS application for oscillation detection is able to distinguish between natural and forced oscillations. In NEWEPS a method that fits a Least Squares Autoregressive Moving Average plus Sinusoid (LS-ARMA+S) model to the PMU measurements data has been used to distinguish between natural and forced oscillations. The method was selected because the LS-ARMA+S model can accurately separate an oscillation from the background noise without losing the modal information contained in the noise at the oscillation frequency.

WAMPAC Solutions

The WAMPAC solutions developed in the project aim to secure post-contingency states of the power system by identifying critical contingencies and suggesting the least expensive set of corrective actions for each critical contingency. The corrective actions can rapidly be deployed to secure the system operation in case when a critical contingency occurs. The solutions utilise optimisation methods based on detailed mathematical models of the system and operate in real-time.

The input to the WAMPAC application is the current operating point, system model data, and a list of contingencies to evaluate. The solution is modular where the first part performs a steady state contingency analysis considering line loading limits, bus voltage limits, and bus voltage stability limits based on the sensitivity indicator SZI. The second part finds the optimal corrective actions for each critical contingency by minimising the overall costs of deploying corrective actions for the operational situation evaluating a set of most effective corrective actions. The set of most effective corrective actions are chosen by sensitivity analysis which is performed as a first step in the optimisation. The developed method is integrated as an independent application into the NEWEPS Test & Demonstration platform.

The developed solutions highlight that WAMPAC solutions can enable a secure increased utilisation of the power system.

Conclusions and future outlook

The NEWEPS project represents a significant advancement for methods enabling a secure operation of the increasingly complex power system. The integration of WAMS and WAMPAC solutions within the NEWEPS Test & Demonstration platform provides a robust foundation for future enhancements and real-world applications.

The project demonstrates the potential for advanced monitoring and control systems to improve the reliability and efficiency of the power grid, paving the way for a more resilient and sustainable energy future.

This report concludes with an outlook, including a roadmap for deployment and future development towards a future Nordic WAMS & WAMPAC system.

Acknowledgement

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Expressions used in the report

Expression	Comment
AA	Adaptive Approach based VSI
AD	Adaptive Method based VSI
AI	Artificial Intelligence
ARMA	Autoregressive Moving Average
EKF	Extended Kalman Filter
EMS	Energy Management System
EMT	Electro Magnetic Transient
ENTSO-E	European Network of Transmission System Operators
FFT	Fast Fourier Transform
GPS	Global Positioning System
GUI	Graphical User Interface
HiL	Hardware-in-the-Loop
HVDC	High Voltage Direct Current
ICCP	Inter-Control Center Communications Protocol
ICT	Information and Communications Technology
IED	Intelligent Electronic Devices
IRIG-B	Instrumentation Group time code B
ITM	Ideal Transformer Model
Jitter	The deviation from the true periodicity of a presumably regular signal
Kafka	Open-source distributed streaming system used for stream processing
LS	Least Squares
MU	Merging Unit
N-1-fault	N-1 criterion states that the system should be able to continue operating without any loss of service if one component fails
N4SID	Numerical algorithms for subspace state space system identification
NSGL	National Smart Grid Laboratory
OPAL-RT	Company delivering Real Time Simulator
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
POD	Power Oscillation Damping

PSS	Power System Stabilizer
PSS SINCAL	Power system planning and analysis software
PSS/E	Power System Simulator for Engineering
Python	High-level, general-purpose programming language
RoCoF	Rate of Change of Frequencies
RTS	Real-Time Simulator
RTU	Remote Terminal Unit
SCADA	Supervisory, Control And Data Acquisition
SCOPF	Security Constrained Optimal Power Flow
SSE	Static state estimation
SSI	Stochastic Subspace Identification
SV	Sampled Values
SZI	S-Z sensitivity Indicator based VSI
TOPS	Tiny Open Power System Simulator
TSO	Transmission System Operator
UKF	Unscented Kalman Filter
VSA	Voltage Stability Assessment
VSI	Voltage Stability Index
WAM	Wide Area Monitoring
WAMPAC	Wide Area Monitoring Control and Protection
WAMS	Wide Area Monitoring System
WASA	Wide-Area Stability Assessment

1 Introduction

Power systems are changing and are becoming increasingly volatile, influenced by larger share of variable renewable generation, decreased conventional generation, more power electronics, increased market integrations, and increased load variations. In addition, major changes in the power flows via HVDC (high voltage direct current) interconnectors and variations in wind generation increase the complexity of system balancing and affect congestion handling. These changes lead to challenges and affect the stability of the power system and its dynamic behaviour. In order to handle these challenges, control centers require new applications and methods for improved on-line monitoring and control to ensure the secure operation of the increasingly complex power system.

This report presents results from the common Norwegian-Swedish research project “NEWEPS” – Nordic Early Warning Early Prevention System, carried out between 2021 and 2024. The project has been a collaboration between the transmission system operators (TSO) Statnett and Svenska kraftnät, the research organisations RISE Research Institutes of Sweden and SINTEF Energy Research, and the technical universities KTH Royal Institute of Technology and NTNU Norwegian University of Science and Technology.

The NEWEPS project have focused on how increased utilisation of information from Phasor Measurement Units (PMUs) in the control room can give an increased situational awareness and provide decision support to the system operators. Despite the fact that synchrophasor measurements from PMUs and dynamic state estimation techniques have been available for a considerable time, most TSOs have not yet deployed these in operation. Thus, operation of the power system is still mainly based on steady state conditions, lacking the capability of observing and/or predicting dynamic events. The reason behind this may be both that dynamic characteristics leading to disturbances are under most operational conditions not predominant in power systems with high share of rotating reserves, as well as insufficient trust in PMU based solutions to allow integration into the critical systems for power system operation. Compared to more conventional measurement systems, PMUs provide information of the voltage and current phasors and have very precise and synchronised time logging enabling more detailed information of the power system status. Using measurements from PMUs enable identification of the power system dynamic behaviour, improving the assessment of true stability margins, which is the aim of a wide area monitoring system (WAMS). Further advancements, including also control and protective actions, are typically referred to as wide area monitoring control and protection (WAMPAC) solutions. The general focus of the NEWEPS project has been on PMU utilisation and WAMS, with an addition focus dedicated to WAMPAC.

The main goal of the NEWEPS project was to develop and demonstrate an information system based on technical methods for power system monitoring, decision support and control for the Nordic power system. The goal was also to increase the competence of involved Nordic actors (universities, TSOs and research institutes).

In addition to building of competence and sharing of knowledge through publication and workshops, the NEWEPS project had the following secondary goals defined to support the main goal:

1. Develop a prototype for a Nordic system for early warning and early prevention of unwanted system states such as instability and system collapse. The prototype will assess real high-resolution operating data as well as emulated operating data from simulated scenarios.
2. Establish specifications for performance assessment and develop methods for testing applications. Create important realistic test scenarios, e.g. 100% renewable, operating point closer to instability, measurement noise, etc.
3. Analyse interoperability between systems and develop mechanisms for secure information and data exchange of power system data. Implementation to enable information and data flow in the platform.

4. Develop visualisation methods to give a clear picture of the system state based on the stability phenomena. Develop decision support for the operators and their control measures in real time.
5. Prepare a roadmap for further development and implementation.

The project was formed in five work packages:

A. **Data platform, demo and testing**: led by Statnett and Svenska kraftnät, evaluating data and functionality requirements, and enabling tests and demonstrations on real data.

B. **Application development, Voltage stability**: led by NTNU, development of voltage stability monitoring methods and implementation in the NEWEPS Test & Demonstration platform.

C. **Application development, Oscillation**: led by KTH, development of oscillation monitoring methods and implementation in the NEWEPS Test & Demonstration platform.

D. **Coordination and visualisation**: led by SINTEF and RISE, development of the NEWEPS Test & Demonstration platform, including methods for coordination and visualisation.

E. **Road map, coordination, dissemination, and project management**: led by Statnett and Svenska kraftnät, coordinating and supporting the project efforts.

This report is structured in the following way:

Chapter 2 presents a *Vision of a Nordic WAMS and WAMPAC*, describing the architectural, data quality, and visualisation perspectives of future Nordic WAMS and WAMPAC systems, which has been a basis for the developments in the NEWEPS project.

Chapter 3 presents the *NEWEPS Test & Demonstration platform*, which is the platform developed and used within the NEWEPS project to enable testing and validation of WAMS and WAMPAC applications and demonstration and visualisation of results for users and need-owners.

Chapter 4 describes the *WAMS Applications* developed in the project, where focus has been on voltage stability monitoring, monitoring and detection of natural oscillations, and detection of forced oscillations and resonances.

Chapter 5 presents *WAMPAC Solutions*, developed to address mitigative solutions to increase the security of the grid when operated with increased utilisation.

Chapter 6 presents the *Conclusions and future outlook*, connecting the main achievements of the NEWEPS project to possible steps for future deployment and developments of Nordic WAMS and WAMPAC systems.

2 Vision of a Nordic WAMS and WAMPAC

2.1 Introduction

The development and deployment of Nordic WAMS and WAMPAC solutions require thorough background investigations and assessment. Various alternatives to enable the operational support should be evaluated to provide the trust in the systems needed to integrate this type of solutions into the critical systems for power system operation. This chapter presents several perspectives which are considered of importance in the development and deployment of Nordic WAMS and WAMPAC systems. Firstly, architectural perspectives are presented and related to the NEWEPS project, where considerations regarding several architectural capabilities are presented, ranging from basic WAMS solutions to state estimation integration and advanced WAMPAC. Secondly, data quality perspectives are discussed, including methods to provide improved quality and reliability of data. Thirdly, a visualisation perspective on how to present WAMS and WAMPAC data for the operator is described, where concepts have been developed in collaboration with operators.

Several of the perspectives presented in this chapter have been taken further into the development of the NEWEPS Test & Demonstration platform.

2.2 Architectural perspectives

2.2.1 Introduction

This section elaborates architectural perspectives in a future integrated Nordic WAMS platform. It does not recommend specific implementations of the capabilities but gives a set of considerations to be answered when staging from traditional measurement WAMS implementations to advanced WAMS implementation with state estimation capabilities.

Parts of the architectural capabilities proposed are implemented and verified in the NEWEPS Test & Development Platform further described in chapter 3, others are a subset of general best practices for system integration and platform virtualisation. The input is based on elaborations in the NEWEPS project, on results from previous research projects such as SPANDEx[1], Sparc[2] and ASAP[3], and on results of vendor input (interviews and publicly available information). The most valuable part of this work is considered to be the *problem statements* and the *considerations* presented in each of the subsections.

The scope of NEWEPS Test & Demonstration platform is to provide advanced real-time assessments of measurement to detect and assess dynamic power system instabilities using time synchronisation as a reference (synchrophasor data provided by PMUs -> Wide Area Measurement System). The objective of a Wide Area Measurement System (WAMS) is also to minimise conflicts between presented Wide-Area Stability Assessment (WASA) and results from other operational information system, EMS (Energy Management System), and how the WASA may achieve higher quality/integrity/predictability/etc. - e.g. if integrated with a state estimator providing load flow and topology results.

[1] SPANDEX (Control Centre Platform for Synchrophasor and PMU Applications, Integration and Data Exchange): https://prosjektbanken.forskningsradet.no/en/project/FORISS/256334

[2] SPARC (SynchroPhasor-based automatic real-time control): https://prosjektbanken.forskningsradet.no/en/project/FORISS/280967

[3] ASAP (Advanced System protection schemes Applied in the Power grid): https://prosjektbanken.forskningsradet.no/en/project/FORISS/327728

This section intends to elaborate and describe technical integration dependencies between functional capabilities in a "basic" WAMS, new advanced capabilities for WAMS, and supporting capabilities in other operational systems like EMS. The objective is through cross domain knowledge sharing to identify design criteria for a future *Nordic WAMS system architecture*.

The descriptions elaborate on data flow and integration with external systems, which dependencies are beyond the delivery of the NEWEPS project. However, nevertheless architectural dependencies are a potential necessity to consider, to ensure a consistent application architecture and a robust system architecture of a future Nordic WAMS. This affects the objective and architecture of:

- Situational awareness and visualisation - a set of techniques to present the assessed events in facilitated dashboard displays (alarm lists, trends, plots, maps, etc).
- Coordination - an application at each TSO that consist of a set of application services that:
    - evaluate the results from the dynamic stability assessment (alarm/event, its criticality and root cause),
    - present the results in the user interface in a prioritised and consistent way, - and
    - recommend control actions (open-loop control) or execute them (closed-loop control).
- Supporting applications e.g. like data pre-processing, bad data assessment, contextualisation, etc).

In addition, it is an overall objective to assess the proposed Nordic WAMS system architecture capabilities against hypotheses and results made throughout the NEWEPS project and on a reasonable level to define final implementation constraints.

Despite that synchrophasor measurements from PMUs and dynamic state estimation techniques have been available for some time, most legacy SCADA/EMS are monitoring steady state conditions and lacks the capability of observing and/or predicting dynamic instabilities. The reason may be that dynamic instabilities leading to disturbance under most operational conditions are usually not predominant in a power system with a high share of rotating reserves. For the same reason, dynamic instability alarms can be perceived as disturbing to an operator, at least if the cause is not identified and if false positive alarms predominate. This motivates a flexible application architecture that allows a gradual implementation and adaption of application services possible to be individually monitored, tuned and if necessary be replaced when new technology and knowledge is available (*interchangeability*).

Though the functional architecture mainly will focus on coordinated WASA between the Nordic TSOs, it also applies for coordination between TSOs and other control centres (producers, DSOs, etc.).

In addition to *elaborating and detailing* the *dataflow diagrams*, each architectural perspective described will formulate anticipated gains and risks in the functional implementation (*hypotheses*) and raising questions for further project clarifications (*considerations*).

The section is structured according to the following *Architectural Perspectives*:

1. **Improved Assessment in Basic WAMS** defines the set of common concepts and/or capabilities of commercial WAMS used for Wide-Area Situational Awareness. Some of these capabilities are discussed in various parts of the NEWEPS project.
2. **Coordinated Assessment between the Nordic TSOs** defines the capabilities of information exchange between the Nordic TSOs autonomous WAMS, with objective to get a consistent situational awareness (including criticality, root causes and best preventive actions) of dynamic instabilities in the Nordic power system between power system operators.
3. **Consistent Situational Awareness** addresses the problem with inconsistent/conflicting sources of information, potentially confusing the operator in open-loop operation and a necessity to solve in automatic/closed-loop operation.

4. **WAMS and State Estimation** discuss how the functional dependencies between WAMS and results from a state estimator influences the architecture, and how external systems like the network applications in a traditional EMS may improve their results using synchrophasor measurement with high quality/integrity as input, and requirements to the WAMS to achieve such measurement quality.
5. **Wide Area Control and Protection** elaborates capabilities to orchestrate a closed-loop control, both if distributed or centralised. It also elaborates on system capabilities to integrate necessary infrastructure for off-line analytics and machine learning to lower computation cost in real-time and achieve better results.
6. **Communication Control** discuss techniques to control integrity, latency, jitter (the deviation from the true periodicity of a presumably regular signal) and data loss in wide area communication networks and elaborates WAMS role to orchestrate a Software Defined Network (SDM) to achieve higher network determinism.

In addition to the architectural perspectives, other general capabilities are considered important for a Nordic WAMS platform:

- A low latency streaming integration architecture (as e.g. Kafka), with a set of well-defined protocol adapters (e.g. IEEE-c37.118.2, IEC 60860-5-104, messaging e.g. using Web Services/REST, data exchange of estimator results, etc.)
- A virtualised computing environment (as e.g. Kubernetes or OpenShift): an orchestrated microservice platform for scalability and extensibility, preferably containerised to allowing portability (running the code on different HW/OS at the different TSOs).
- In-built redundancy and load balancing
- A suitable framework for advanced real-time user interfaces.
- High volume database for high resolution time series data; suitable for machine learning.
- Flexible and scalable test capability to verify changes (staging environment); Preferably with simulation capability (generating synthetic data for consistent unit testing).
- A development platform managing code, platform integration and deployment.
- Information Architecture: Information models, Labelling and Information schemes, engineering capability for model management.
- Cyber Security capabilities to ensure integrity, availability, and confidentiality.
- Platform monitoring capability (operational availability, anomality and fault detection, performance metrics, etc.)

The developments in the NEWEPS project have been integrated using Kafka, where implementation and validation has been done using the NEWEPS Test & Development Platform, further described in chapter 3.

2.2.2 Improved assessment in basic WAMS

The general characteristics for a traditional "basic" WAMS is e.g. that:

- It is solely measurement based and not assisted by a power system model or any form of power system state estimation.

- The measurements feeding the stability assessment algorithms are anticipated to be accurate within the requirements in the IEEE c37.118.1 Synchrophasor measurement specification[4].
- The quality condition of PMU measurements refers to the sum of uncertainties in the estimation of the measurement vector in the PMU (Total Vector Error and Frequency Error).
- The measurements are time synchronised within the accuracy of ± 1µs.
- The primary voltage and current measurements are estimated by the PMU application and represented by 3phase vectors in polar or rectangular formats – RMS values and angles (alternatively recalculated to their symmetrical component), and frequency and Rate of Change of Frequencies (RoCoF) (df/dt) of measurements.
- The data rate representing the measurement time series resolution is typically 50 frames per second (fps) in a 50 Hz system but may be higher (< 200 fps) or lower (>1 fps) based on application requirements (WASA use case).
- A time synchronised set of PMU measurements will be used by WAMS applications to determine instabilities, and their criticality.
- The observability (number and placement of PMUs) will determine how effective the WAMS applications are. Observability in the neighbour TSOs in a synchronous control area is usually lower than in the local TSOs area due to the responsibility. The local impact of instabilities may however be the same independently of the origin of the fault.

The PMU is required to estimate correct *phasor measurements* in steady state and dynamic scenarios according to IEEE c37.118.1[5]. If the PMU application is unable to estimate the synchrophasor used on available mechanisms (basic low pass filtering, more advanced preprocessing/filtering technics and estimation algorithm developed by the PMU vendor) and/or timestamp the resulting phasor correctly, it shall be appropriately marked with quality condition *invalid* or *error*.

The applications in a "basic" WAMS are normally highly dependent on the PMUs ability to estimate *synchrophasors* correctly (estimated phasor measurements with a highly accurate time stamp). Compared to EMS applications where SCADA measurements have low time accuracy and the estimated power system state measurements are based on a validated power system model reference, high quality PMU measurements will be sufficient without SE capabilities for many real-time WAMPACS application use cases. However, a state estimator will provide additional benefits for advanced WASA, such as poor data detection and topology awareness as discussed in Section 2.2.3.

Figure 1 shows the components of a "basic" WAMS available from most vendors (green boxes) and architectural concept of improved application modules considered in the NEWEPS project (yellow boxes).

[4] IEEE c37.118.1 (2011) + Amendment 1 (2014) *Standard for Synchrophasor Measurements for Power Systems*, chapter 5 *Synchrophasor measurement requirements and compliance verification*.

[5] IEEE c37.118.1 (2011)+amendment1 (2014) chapter 5.5 *Measurement Compliance*.

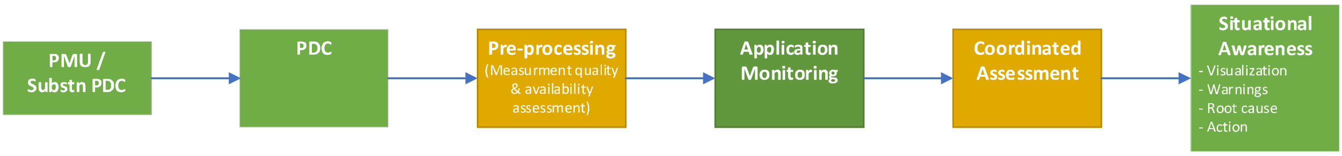

Figure 1: Basic components of a Wide Area Measurement System (green boxes) and additional improved application modules considered in NEWEPS (yellow boxes)

- The "blue arrows" in Figure 1 indicates functional data flow. Physical integration between the components and their dataflow is not necessarily unidirectional. The relation between the functional blocks is elaborated in this chapter.
- The "green components" indicate a functional representation of the typical services in WAMS and may either fulfil their requirements as monolithic applications or virtualised/multiple service instances. The level of virtualisation should be considered by each application requirement to ensure interchangeability.
- The "yellow components" are functional representation of architectural capabilities which traditionally are not found in a system based on "basic" WAMS functionality.

The *Pre-processing* aspect is further described in section 2.3, and the *Coordination* functionality is further described in section 3.4. The multi dependencies between the WAMS & WAMPAC applications and these modules is considered to be the components in the architecture with lowest maturity in the consensus of what a Wide Area Measurement System should achieve. The potentiality of the components is agreed to be highly beneficial by the development in the NEWEPS project but also raises some unknown complexities.

Pre-Processing refers to any evaluation or improvement of the measurement received from the PMU to make a better or more consistent assessment. Including e.g.:

- Evaluating the measurement quality using state estimation methods. The service should handle the re-assessed measurement based on e.g. a set of common rules as – replace and forward the measurement point corrected/estimated value and quality state to the functional application, alternatively withhold the measurement, if e.g. the state estimator does not converge or forward the bad measurement with an appropriate quality state, etc. The more sensitive the algorithm is to bad or missing data, the more important the pre-processing is anticipated to be.
- Contextualise the PMU measurement to make the data more usable/understandable for the various applications. The contextualisation process may also consider other information sources (as the operational Common Information Model, load flow/topology/solved state received from an external state estimation, etc.)

Coordinated Assessment refers to any re-assessments of the information output from the individual applications assessing stability.

- The objective of the coordinated assessment is to synthesise the sum of all information gathered by the PMUs and refined in the applications and improve the information presented for the operator in open-loop control, or for the closed-loop control application. Considering e.g.:
    - If/how the warning is presented, criticality information of the information, etc.
    - If/how a graphical visualisation shall be presented (application to present time series or vectors/values), and/or connecting the warning to the graphical representation (information needed for the operator to navigate between displays).

Hypotheses

1. **Pre-processing module** will improve the output quality from the individual WAMS applications, by:
   - Contextualizing the PMU-data to improve the WASA applications need for data processing, e.g. by simplifying data readability (e.g. transform quality bitmask to states, combine pre- and post-processed quality states etc.), map measurements to power system topology (nodes, area/zones) or branch load-flow, etc.
   - Evaluating and manage bad PMU data quality as measurement chain errors (bad metering transformer, erroneous phasor measurement due to transient noise or non-compliant phasor estimation, etc.) time synchronisation errors (missing or bad time source, non-compliant time synch resulting in excess Total Vector Error[6], etc) or communication errors (loss, latency, jitter) by adding/replacing quality information, inhibit or improve/replace measurements, etc.). Missing, delayed[7] or erroneous measurement input may to varying degrees affect the applications capability to assess dynamics correctly – dependent on the algorithm's sensitivity to such artifacts.
   - The implementation of the pre-processing should weigh the application sensitivity to data artifacts against computational delay introduced, hence the pre-processing method might vary based on the applications requirements.
2. **Coordination Module** will improve situational awareness in WAMS by:
   - Evaluate assessments made by all WASA-applications, prioritise them based on criticality, and propagate the result to operators.
     - In more advanced WAMPAC scenarios, also to evaluate and propose most relevant remedial action to the operator for open-loop control, or to assist automatic control mechanisms for closed loop control.
   - The evaluated assessment should be enriched by metadata for being used for automatic or manual sorting, filtering, and search mechanisms in displays.
     - In more advanced scenarios, a linear/dynamic state estimated coordinated assessment predicting most critical dynamics pr. outage would generate input to the traditional contingency list (most critical outage).

Assisting operator evaluation where power system state estimates is not available by post processing the input from WASA-applications, e.g. by mapping event metadata for assisted or automatic navigation to WAMS Visualisation modules (e.g. as prioritised event lists, pre-engineered graphical displays, or panels/layout of multiple display techniques, etc.). Post processing may in addition synthesise WASA information from other sources evaluating stability (e.g. solved state from an external SCADA/EMS) and resolve conflicts.

Considerations

Coordination and pre-processing should be considered as common services to ensure fast data processing and consistency. Neither a *Coordination* nor a *Pre-processing* Module should be monolithic.

Neither coordination nor pre-processing should be considered as hierarchical services in context to the WASA applications. The WASA apps may provide input to the pre-processing module or be dependent on input from the coordination module. Distinction between WAMS & WAMPAC applications and supporting services as pre-

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[6] Total Vector Error (TVE) ref IEEE c37.11.1 cpt 5.3.1

[7] Communication artefacts as e.g. described in IEC 61850-90-5 (2012) *Communication networks and systems for power utility automation - Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118*, Chapter 5 *Use Cases*, and Chapter 7 *Communication requirements*

processing and coordination may be beneficial from an architectural view and should be promoted but may not always be achievable. The complexity calls for detailed modelling both of information and code.

An implementation of the application complexity discussed in this section in an architecture taking benefit of state-of-the-art platform virtualisation and containerised application in microservice platforms, to offer productivity, automation, and inbuilt capabilities as portability, scalability, interchangeability, etc. Though at the same time it may introduce concerns about e.g. application latency if not managed correctly, and for sure some technical complexity. Hence it requires maturity in both IT development and IT operation (modern development techniques as CI/CD[8], advanced logging and monitoring tools) to obtain e.g. development efficiency and required operational availability. On the other hand, the transformational nature of advanced real-time application platforms may make it hard to obtain the upside of virtualised platforms in monolithic systems architecture.

Cyber Security has not been explicitly addressed in the NEWEPS project. Availability and integrity issues are however important factors and must be complied by all implementations in the distributed system.

NEWEPS project results

Pre-Processing module

A proposed data quality processing method for estimating the dynamics of the transmission grid, verified on a small case study. See section 2.3.

Real-time Kafka Streams

Conceptual verification of virtualised application architecture in real-time with live data:

- Flexible integration architecture verified by using Kafka and Application architecture using Micro services (Kubernetes) discussed in chapter 3.
- Performance metrics verified conceptually by integrating real-time PMU data streams using Kafka streams (and Kafka connect adapter in *openPDC*)[9].

Limitations:

- The test of live stream integration was limited to forwarding data for 3 PMUs. However, by experience PDC relay and the Kafka Streams scales to handle high volume data, though the producing connector (using the Kafka Connect adapter offered by Open PDC) might not. The latter should be optimised by making an improved communication adaptor, which also manage communication security (incl. a redundancy concept).
- Due to application platform time sync capabilities (NTP[10]) increased application latency was not scientifically proven.

Results

- comparing logged PDC average latency (also using NTP) with average latency generated in OpenShift RT summarisation application, the average increased latency appeared to be ~30ms, and

[8] Continuous Integration/Continuous Deployment

[9] https://gridprotectionalliance.org/phasor-PDC.html. Verification made in 2020

[10] NTP 4.0 protocol and synched with *stratum 1* time source

- no visual difference when comparing trend curves in 3rd party real-time WAMS application with Grafana trend curves reading Kafka streams. Considering the refresh rate of both should hence proof added end to end latency lower than 1s.

2.2.3 Coordinated Assessment between the Nordic TSOs

The synchronous Nordic power system is operated by four control entities (TSOs), each having multiple control centres with different responsibilities. The observability of the neighbouring TSOs control area varies. In general, equivalent models are used for obtaining estimated consistent power flow for interchange, and data from a limited measurement set are exchanged to improve the state estimation in each respective system. The equivalent models are lacking detailed information, such as the topology and controlled capacity and how the physical quantities/reserves are connected to the topology. The ability to control the topology and reserves is always the responsibility of the local TSOs, and so is the responsibility to assess and ensure operational and supporting conditions (FCR, short circuit capacity, etc.).

Traditional WAMS methods require PMU-measurements to be exchanged in real-time to the local TSOs WAMS to assess dynamics with origin in neighbouring TSO controlled area. Such assessments at the local TSOs may be improved by exchanging local assessments between the different control centres, which is further described in section 3.4.

The objective of the coordinated assessment is to improve situational awareness and to coordinate manual or automatic actions between TSOs to faster improve the security of the system. This stipulates the receiving TSO to make their local decisions not only based on measurements, but also on assessment results from the remote neighbouring TSOs WAMS assessment. The detailed information from the local assessment may bring a consensus of the criticality and actions being taken in a faster way than doing this manually, which in critical cases may be too late to avoid a major disturbance. Coordination of preventive actions may also restore a secure power system state faster.

Generally, the same basic requirement applies to the non-simultaneous *coordination service* as to a data streaming protocol like IEEE c37.118.2. The exchanged information for external *coordination* must be technically and functionally consistent and explicitly understandable for all parties, implying that:

- The communication protocol requirements must be standardised (data exchange methods, contextualised data as data format/scheme, data flow and error handling, etc.).
- Technical requirements as methods to ensure availability, integrity and confidentiality must be defined.
- Operational requirements must be defined, e.g. as how to: change methods or scheme, perform functional and non-functional verifications, monitor technical and functional error and inconsistencies, etc.

Dependent on the use case, the availability and latency constraints may be limiting factors for the effectiveness of a *coordination service* and should be elaborated.

Figure 2 shows the architectural concept of Nordic WAMS Coordinated Assessment, with focus on the situational awareness.

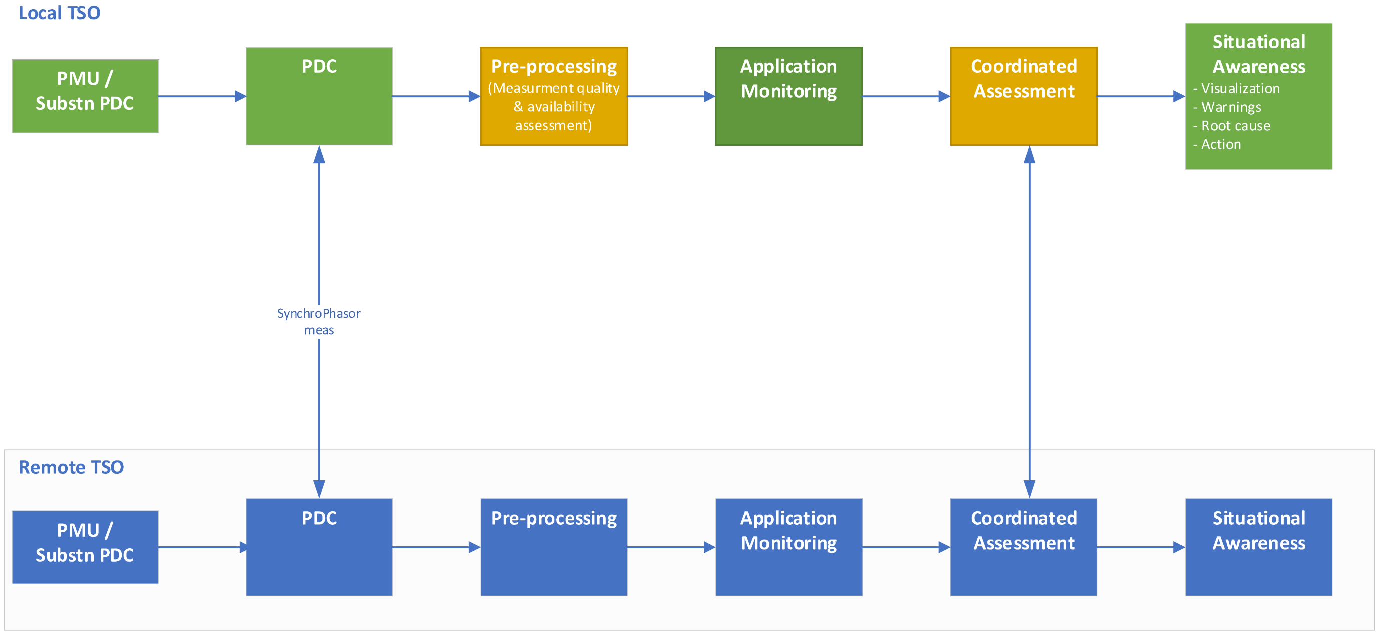

Figure 2: Nordic Wide Area Monitoring System Coordinated Assessment, focused on situational awareness.

Figure 3 shows the architectural concept of Nordic WAMS Coordinated Assessment, including also WAMPAC.

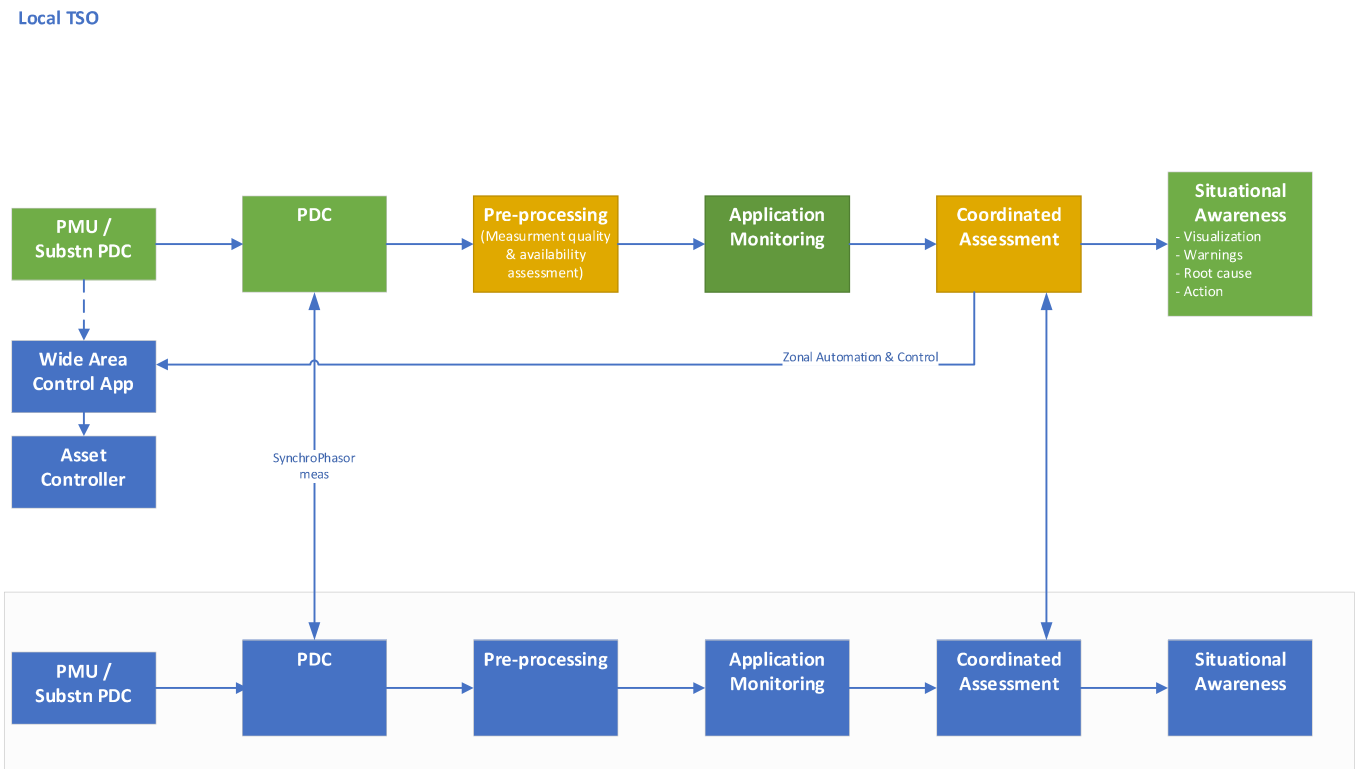

Figure 3: Coordinated Assessment, perspective on Basic WAMPACS/ Closed Loop Control

The coordination may assist both centralised and/or de-centralised/distributed control, with different objective.

Hypotheses

The distributed WAMS system with the proposed coordination capabilities will have advantages compared to local WAMS concepts or a common Nordic WAMS due to the following considerations:

1. A coordinated system as well as a common WAMS for all Nordic TSOs would contribute to better situational awareness. However, depending on whether the coordination functions are sufficient to achieve consistent situational awareness with sufficient integrity, the system architecture in a distributed system will provide better flexibility in the course of innovation and development as well as adaptation to the individual control centre's operating regime.

   A distributed system topology is also anticipated to offer higher availability (fall back from "coordinated WAMS" to "local/uncoordinated WAMS").

   As system integrity is also considered crucial for a Nordic WAMS, a distributed control system is assumed to be advantageous both in relation to the PMU network (communication integrity) and in relation to the integrity of the computing environment. As for SCADA/EMS, one still depends on common policy and rules, and not least common development systems.

2. The communication protocol exchanging local assessment information supports availability and integrity control.
3. The data flow manages efficient technical and functional validation, error handling and traceability/logging.
4. The coordinated Wide-Area applications in each TSO WAMS are based on the same methods and algorithms.
5. The information exchanged is programmatically produced and addressed to receiving twin applications in the remote TSOs.
6. The information exchanged is consistent with, and contextualised and semantically interpretable by the algorithm in the remote twin application.
7. The information exchanged is sufficient for the twin application, to independently or in coordination with its own assessment to:
   a. Evaluate and present which part of the power system that is affected by the disturbance (situational awareness).
   b. Evaluate and present criticality.
   c. Evaluate and present the root cause.
   d. Evaluate and present counter actions, and the counter actions implemented.
8. WAMPAC capabilities include architectural requirements, with the following hypotheses:
   - The coordinated assessment requires the consistency mentioned in the hypotheses above.
   - WAMPAC architecture may require distributed or centralised applications (or both) though a centralised module would anyway be beneficial for flexible coordinate selection and activation of the most appropriate controlled equipment according to operational conditions.
   - A distributed architecture has in addition specific requirements not elaborated in this architecture (e.g. how to achieve a reliable and flexible communication architecture).

   See also section 2.2.6 on *Wide Area Control and Protection*.

Considerations

The level of autonomy may vary between different applications, and may gradually mature from:

- Pre-formatted or manually entered situational awareness information by operators. Control actions manually assessed and manually activated by operators.
- Situational awareness programmatically produced and presented but manually assessed by operators. Control actions manually assessed and manually activated by operators.
- Situational awareness programmatically produced, assessed, and presented. Control actions automatically assessed and presented but manually activated by operators.
- Situational awareness programmatically produced and assessed. Control actions automatically issued (closed loop control).

When a preventive action requires an operator decision process, the results from application assessment should programmatically provide metadata to improve navigation (drill-down), by e.g. soft- or hard-linking to displays:

- A link from tabular information as alarm/event lists or coordinated message list to graphical presentation with trending time series, time series diagrams, contour layer diagram, etc.
- Link from alarm/event list to predefined dashboards (set of panels/displays components), focusing on situational awareness.

NEWEPS project results

Coordination module

- To verify the coordination module functionality, implementations in the NEWEPS Test & Development platform have been done demonstrating two different coordination concepts. See chapter 3.4.

2.2.4 Consistent Situational Awareness

A traditional SCADA/EMS has complementary real-time capabilities to WAMS, mainly due to different observability (what you can observe based on difference in telemetered measurements and applications to assess the power system state). This section elaborates the functional capabilities to obtain consistency to the observability.

The inconsistency need not only stem from the difference between measurement inputs (e.g. different measurement types, locations, data rate, etc.), but also from erroneous or deviant data. Such conflicts should be handled to ensure that operators are not exposed to misunderstandings.

Control of power systems in normal operation is based on a "compressed view of reality" (operationally paradigm), e.g. observed voltage lies within certain thresholds. Based on what may be observed and which applications used to assess the power system state (algorithms for assessment and intelligent alarms, visualisation techniques, etc.), a limited set of observed information (key parameters) must be selected and visualised to form a consistent understanding of the condition of the power grid. Even a detail such as deviant use of colour can lead to inconsistent perception.

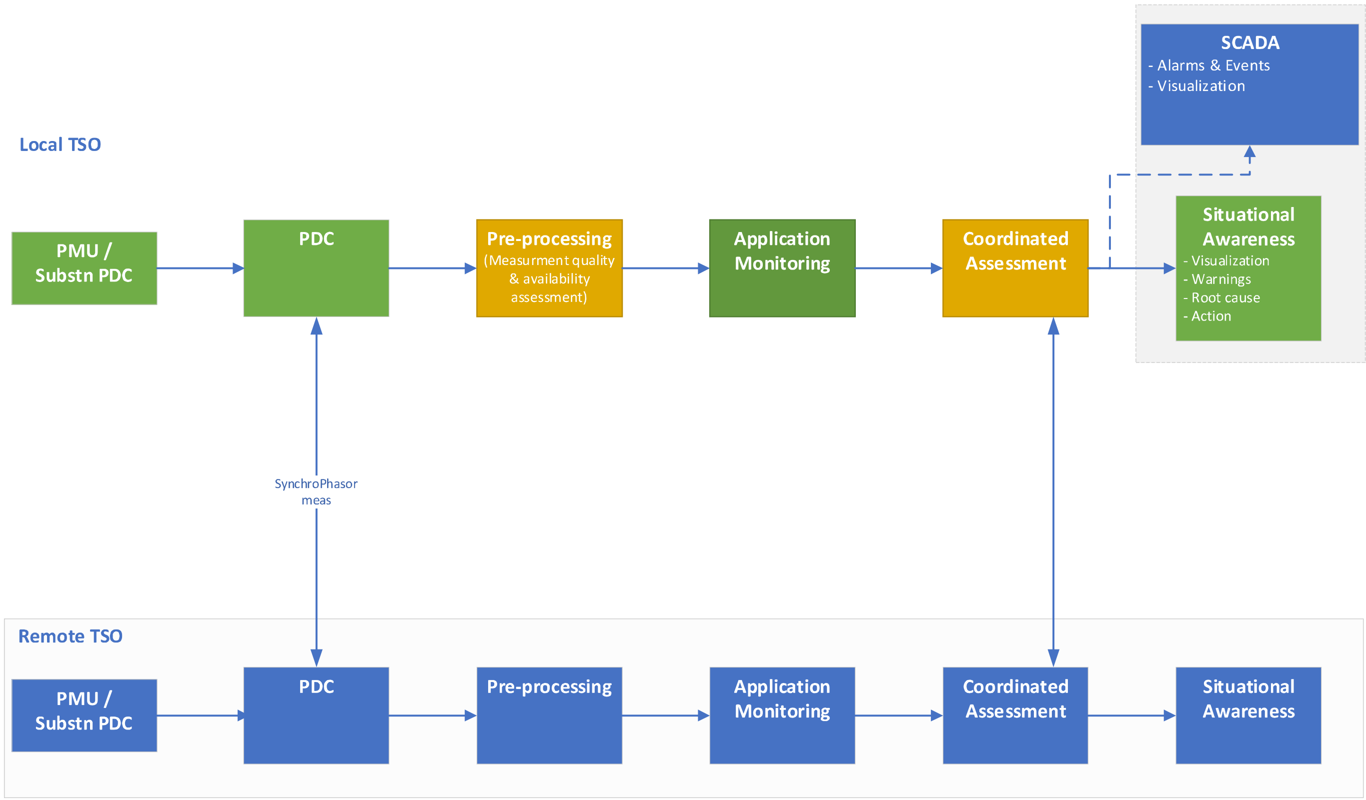

Figure 4: Coordinated Assessment, perspective on WAMS/Situational Awareness consistent across systems.

Hypotheses

As for any of the architectural perspectives considered, the control system may coexist of independent SCADA/EMS and WAMS. However, efficient operation requires unambiguous input to the operators to avoid confusion of the system state. Hence,

- Alarms and warnings (or other critical situational awareness messages) must not be conflicting and require explicit action.
- Messages must be necessary and have the objective to increase situational awareness.
- Application assessing power system dynamics should also report the criticality of the dynamic conditions. The coordination must be capable to assess input from multiple applications to only present the necessary alarms and/or control action. This capability requires a consistent modelling of the information presented for the coordination module.
- When introducing observability of complex dynamic conditions, the system should be flexible to gradually introduce complex conditions to operators with various experience. Typically starting with alarms of the most critical conditions and well-structured display navigation to seek more information (drill down capability) eventually also providing key parameters in the system overview displays.

Applications in a solely measurement-based system may require more consideration of an operator than if it is assisted by state estimation. Hence

- WAMS assisted by state estimation will be more efficient and effective by providing:
  - better detection and handling of bad data (which else can lead to false alarms),
  - better root cause analysis,
  - better assessment of proposed control action.

- A dynamic state estimator will improve the Wide Area Stability Assessment even more (compared to a state estimator only considering static models). Hence also improve the situational awareness by
  - providing better assessments of all above,
  - is required for assessing dynamic conditions in the contingency analysis.

Considerations

Until the rapid changes in power system operation motivated by the green shift, WAMS has been considered complementary and even unnecessary in TSOs power operation – at least in the Nordic synchronous area. Here the dominant large hydro and nuclear based power generation and their strong capabilities for primary regulation have managed most critical dynamic instabilities resulting in limited disturbances. The lack of tools for observing and presenting dynamic conditions has kept the dynamic state hidden for the operators in power system fault conditions. Though WAMS tools have been commercially available for decades, bringing the dynamic conditions into awareness should hence be considered with the problematic nature of digital transformations.

WAMS features should be implemented with

- a short-term goal of assuring the operator of the dynamic conditions of the power system and to build knowledge.
- a medium-term goal for the operator to prevent instability from occurring and to take correct measures if it does.
- a long-term goal of automating countermeasures when critical dynamic conditions occur.

Hence

- The awareness of dynamic assessments should gradually be introduced in the control centre.
- The warnings should be consistent without too many false alarms and conflicting information.
- The warnings should be guided with
  - an assessed criticality,
  - the root cause, and
  - relevant actions to improve the situation.

The architecture should allow all applications to operate independently, but consistently.

- All applications should present information consistently (provide metadata according to a scheme) for the coordination module to assess how to report sufficient information to the operator to respond efficiently (filtering to avoid information overflow).
- A coordination module should also manage leaving alarms.

The architecture should ensure system ergonomics to be consistent, e.g.

- Information should be presented consistently (how lists are organised, discrete and analog values are coloured, audible signals presented, etc.). Preferably the operator should not be aware of which system is presenting which information.
- Navigation should be consistent and have similar behaviour (e.g. automatic display of relevant high-level information, "drilldown" - e.g. right mouse click on a warning should present navigation options to generic displays/dashboards showing, etc.).

The model-based assessment in traditional SCADA/EMS without WAMS capabilities is mostly blind to dynamic conditions, both in disturbance situations (outages) and to control errors (misconfigured equipment controller) until a fault occurs. The measurement-based assessment in traditional WAMS (without State Estimation) is however mostly blind to the physical changes in system topology (breaker trips) and have no assessment of safe operation and contingency warnings about consequences of loss of generation or branches (lines and power transformers).

The architectural consideration on Consistent Situational Awareness anticipates that the divergent capabilities between a traditionally SCADA/EMS and may lead to inconsistent or even conflicting presentation of information of power system state if this is not considered in the implementation.

Hence a coordination module should have the capability to ensure that the synthesis of the alarms from the two systems is consistent. This would require:

- message exchange capability between the two systems,
- labelling and information schemes.

As this section only considers the architectural capabilities, the system implementation will not be concluded. However, the following points are required to be part of the WAMS implementation decision process:

- Separate or integrated WAMS and SCADA/EMS
- In house development, or tuning 3rd party tools
- Engineering capabilities (reuse engineering for SCADA/EMS/CIM support – mandatory if WAMS state estimation is implemented)

NEWEPS project results

Kafka topics for alarms and messages have been implemented in the NEWEPS Test & Demonstration platform.

2.2.5 WAMS and state estimation

Generally, power system state estimated with any technique will benefit of available synchrophasor data of high quality (fulfilling the standardised requirements). Of different reasons they do not always do that, e.g. due to erroneous measurement transformers, non-compliant PMUs, anomalies in the time source (time reference fault without faulty states), and artifacts like unavailability (e.g. due to HW or communication faults) and latency.

The simplified data models in traditional WAMS narrow the opportunities of e.g. root cause assessment and proposing of control actions. Advanced WAMS application assessing dynamic conditions will greatly benefit from a state estimator providing topology awareness and power flow.

The section addresses architectural perspectives and describes on a high level the differences between static state estimation and:

- Improved static state estimation (Figure 5)
- Advanced WAMS improving the traditionally measurement based dynamic assessments with various state estimation techniques (Figure 6)
- Opportunities and challenges with common vs. separate state estimators/ techniques in the different control systems.
- The dependency between state estimation results and WAMPAC to achieve flexible control schemes (discussed in section 2.2.7)

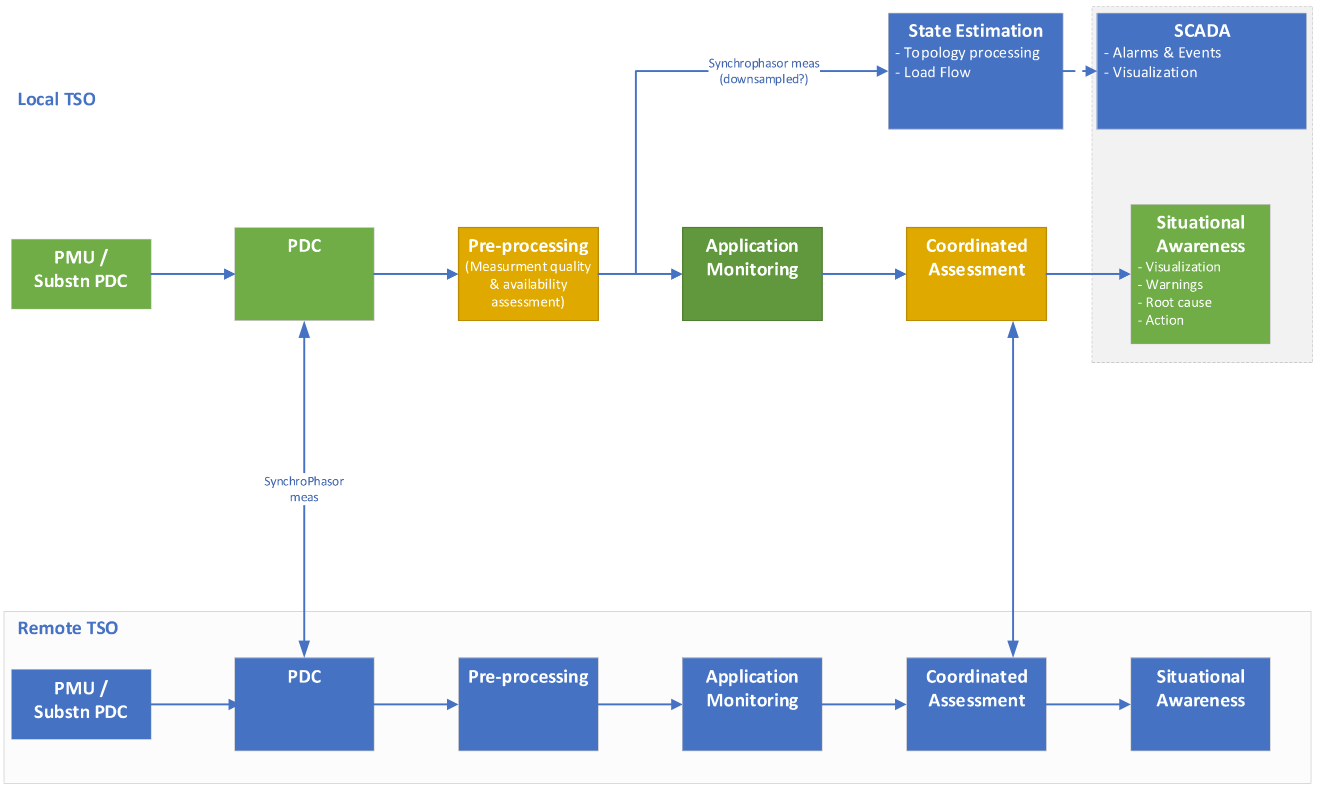

Figure 5: PMU measurements and WAMS improving system state estimation.

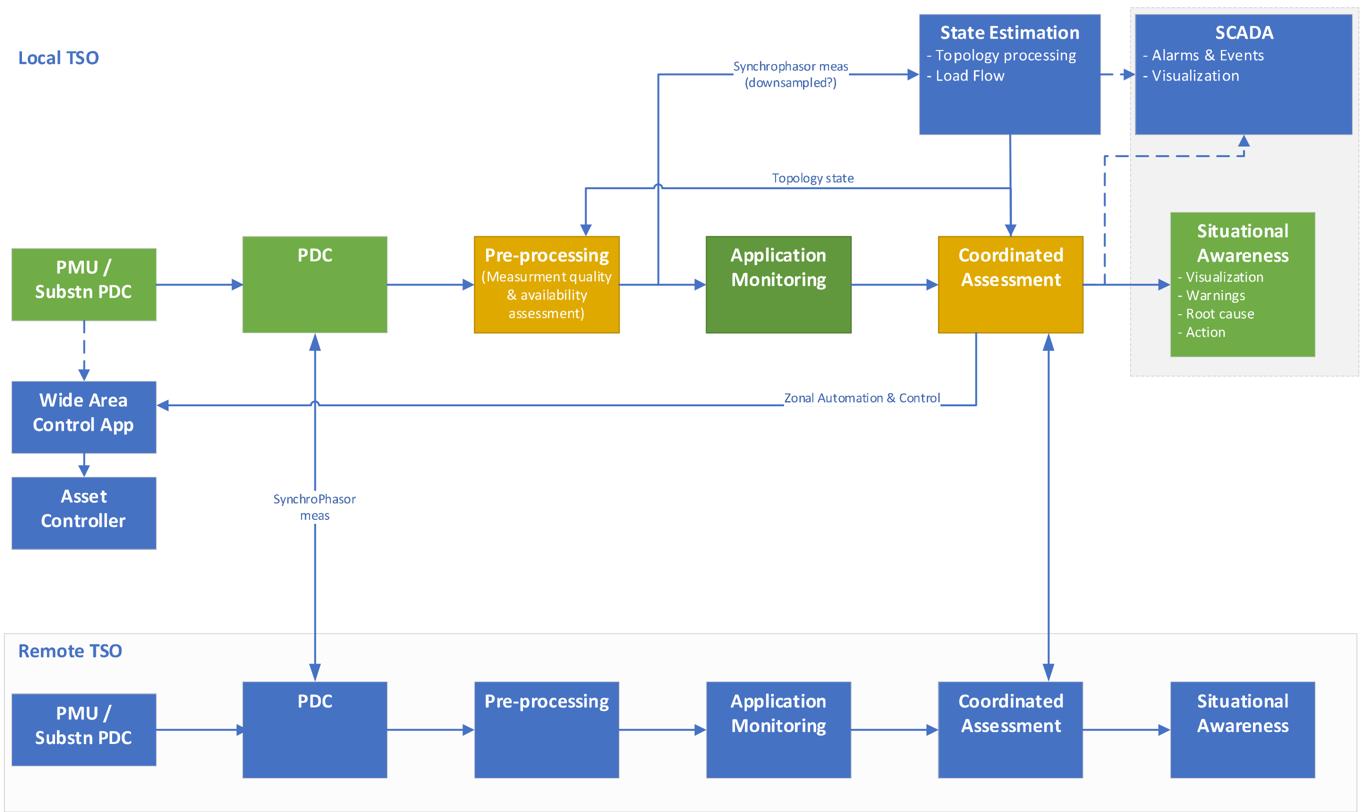

Figure 6: Advanced WAMS – Measurement based assessment improved with power system state estimation

Short introduction to state estimation

State estimators comprise the following functions:

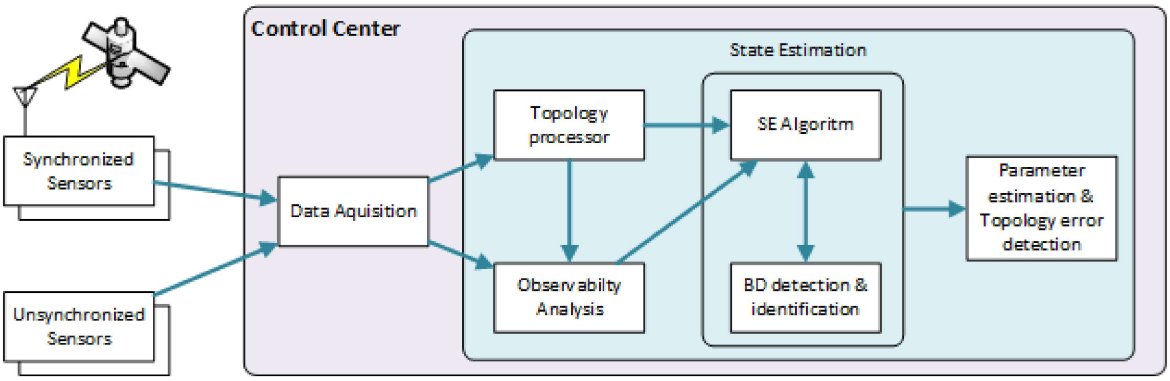

Figure 7 State estimation component overview.

Topology processor: the status of switches and circuit breakers are processed to determine the current network topology.

Observability analysis: the observability of the system for executing state estimation is verified by analysing accrued field measurements. In the case of insufficient measurement redundancy, full observability of the network is not achieved; thus, observable islands must be detected for the execution of state estimation, or observability is reinstated using pseudo-measurements.

State estimation (SE) algorithm: an optimisation process that utilises the aggregated real-time measurements in a certain time frame and provides the estimated state of the network. The random noise (due to instrument transformers, communication errors, limited meter accuracy etc.) intrinsically existing in field data is filtered out; then, these data are used to calculate the most probable operating state of the power system.

- Parameter Adaptation: Unobservable network islands may be substituted by replacement values from schedules[11].
- Network Model Builder: simplifying the internal "Node-Breaker" model to a computable "Bus-Branch" model.
- Models for state estimations:
  - *Static state estimator* estimates the current operating condition of the power system at a particular moment in time, assuming that the system is in a steady state. The system's state is assumed to be constant over time (or varying very slowly), with no significant changes in system dynamics (reiterates typically with a 5-60 second cycle time). A static state estimate will significantly improve with synchrophasor measurement data (both voltage magnitudes, phase angles, eventually also current measurements - with a data rate relevant for the state estimator cycle time) compared to SCADA data and typically uses static models and estimation methodology like least squares methods. See topology described in Figure 5. The state estimation will in *steady state* assume that the system is linear and under normal operating condition (the dynamics of generation, load, and network conditions are not changing rapidly) and without large disturbances. A contingency analysis application may however estimate the

[11] Planning data as Scheduled load and production, Scheduled outages and/or pattern data where telemetry/information missing breaker status, measured power production and load, regulator setpoints, etc.

power flow following loss of (each single) branch, load and generation and report the most critical contingency (e.g. if they are managed by the N-1[12] criteria) in a prioritised order.

- *Dynamic state estimation* considers time-varying conditions of the power system by estimating the grid's state over time, capturing the dynamic behaviour (impact of disturbances, system inertia, and control action). These include not only the bus voltages and power flows but also the system's dynamic responses, such as rotor angles, generator speeds, and other variables related to system inertia and dynamics. Modelling such dynamic parameters will make the state estimator capable to assess the contingency applications and to report critical dynamic conditions during disturbances. The dynamic state estimation requires voltage and current angle measurements to determine the power system dynamic state. The data rate and reliability of the synchrophasor measurement depends on the dynamic phenomena to detect (exemplified in [13]). The dynamic state estimation often relies on advanced filtering techniques, such as EKF (Extended Kalman Filter) or Unscented Kalman Filters (UKF).

Bad Data (BD) detection and identification: an algorithm that enables detection, identification, and elimination of gross measurements in the dataset, based on the statistical properties of measurements. Depending on the employed state estimation algorithm, this step may be integrated directly into the estimation process, or it can be a post-processing step; in the latter case, if bad data are detected and eliminated, the state estimation process is repeated.

Topology error identification and system parameter estimation: like the process of handling bad data, the state estimation results are analysed to diagnose errors in the assumed network topology due to erroneous reporting of the breaker states. Finally, parameter estimation is executed to extract the updated (most probable) values of network parameters based on the state estimation solution.

Hypotheses

WAMS systems will benefit from state estimation integration in several different ways, such as:

- Ensure integrity in the measurement-based assessments (detection of bad input data).
- Better support root cause analysis and assess possible measures.
- Enable a better preparedness analysis by predicting the consequences of a disturbance.
- Make it possible to implement flexible control schemes with closed loop control.

WAMPAC will be difficult to implement without state estimation/topology information and will have to be based on static configuration.
Without state estimation, the control system must be manually configured by the operator based on the actual operating condition and monitored to avoid an unwanted effect if activated under other operating conditions. This will limit the number of possible settings and give very little flexibility.

Any state estimator algorithm will benefit of the time synchronised measurements from PMUs.

[12] The N-1 contingency criterion refers to a power systems ability to operating safely after a single line, transformer, generator loss.

[13] IEC 61850-90-5 (2012) Communication networks and systems for power utility automation - Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118, Chapter 5 Use Cases, and Chapter 7 Communication requirements.

Considerations

Figure 5 and Figure 6 do not provide guidance as to whether one must use a common or separate state estimator in different control systems (as SCADA/EMS and WAMS). Neither has any marked maturity analysis to consider if the requested functionality is available in 3rd party solutions, or if this strategy requires in-house developed solutions, been made. Either way, they all will introduce benefits and complexities:

Common state estimator for SCADA/EMS and WAMS

(+) Consistency and reusability

(+) Reduced cost due to common engineering and tuning (compliance to portable formats as CIM[14] would significantly reduce the data engineering complexity in multiple systems)

(-) It may be difficult to achieve due to interoperable integration requirements for state estimators and applications are not available. One can therefore assume that complex third-party SCADA/EMS solutions will directly or indirectly dominate the functionality that can be achieved in a common state estimator solution.

Separate SE for SCADA/EMS and WAMS

(+) The flexibility to utilise state estimator capabilities for not of the shelf WAMS application

(–) Consistency must be handled.

Third Party Solutions

(+) Consistent solutions offering solutions according to marked requirements

(+) Larger SCADA/EMS suppliers have data exchange capabilities, e.g. to export solved state and topology[15] according the CIM standards

(–) Do not necessary offer customer flexibility for exploring innovative solutions, as e.g. a coordination module as discussed in section 2.2.3.

(–) No in-depth market analysis has been done, but both WAMS and SCADA/EMS suppliers may have an inability to adapt their applications to other state estimator solutions, for example due to

- lack of modularity (access to each subcomponent in the state estimator solution – described in Figure 7 above)
- lack of integration support (interfaces/APIs, e.g. to exchange estimator results),
- the supplier's market segment does not have the same requirements (e.g. different requirements to applications for stability assessment and instability situational awareness in SCADA/EMS).

In-House development

(+) Offers the flexibility to implement customised network applications, with potentially high business value.

(–) Dependency on availability of in-house resources.

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[14] IEC 61970 Energy management system application program interface (EMS-API)

[15] IEC 61970-456 Energy management system application program interfaces (EMS-API) – Solved power system state profiles,

Steady State estimation

(+) The estimated power system state results offer model parameters, topology and solved power system state for small-signal stability/steady-states (e.g. power flow) exchanged for Network analysis application to use (modelled and exchanged e.g. according to CIM[15]).

(−) Do not offer estimation of dynamic conditions.

Dynamic State Estimation

(+) The estimated power system state results offers model parameters, topology and solved power system state for both small-signal and transient stability exchanged for Network analysis application to use (modelled and exchanged e.g. according to the IEC 61970 CIM specification [15, 16]).

(−) The modelling for assessing dynamic stability for converter-based resources is not mature (only project-based models)[17]

NEWEPS project results

Bad data assessment is discussed in section 2.3.4.

2.2.6 Wide Area Control and Protection - WAMPAC

The use-cases for closed-loop control and the impact on the proposed architecture have been functionally elaborated in the NEWEPS project.

Figure 8 describe the following aspects discussed in the project:

1. Enrichment of WAMS applications with estimated power system state results for mastering *flexible control schemes* (as discussed in section 2.2.5).
2. Coordinated Assessment (as discussed in section 2.2.3) mastering centralised flexible control schemes or activating distributed static control schemes ("Zonal Automation and Control").
3. Distributed Wide Area Control Apps are controlled by centralised WAMS dynamic assessment (or controlling asset/equipment controllers via the distributed Wide Area controller)
4. Off-line analytics (Machine Learning) sharing data labels describing off-line assessed instability signatures.

[16] IEC 61970-457 Energy management system application program interfaces (EMS-API) – Dynamics profile,

[17] IEC 61970-457: "*The HVDC dynamics models are a complex domain in which there are no models that are approved or widely recognised.*"

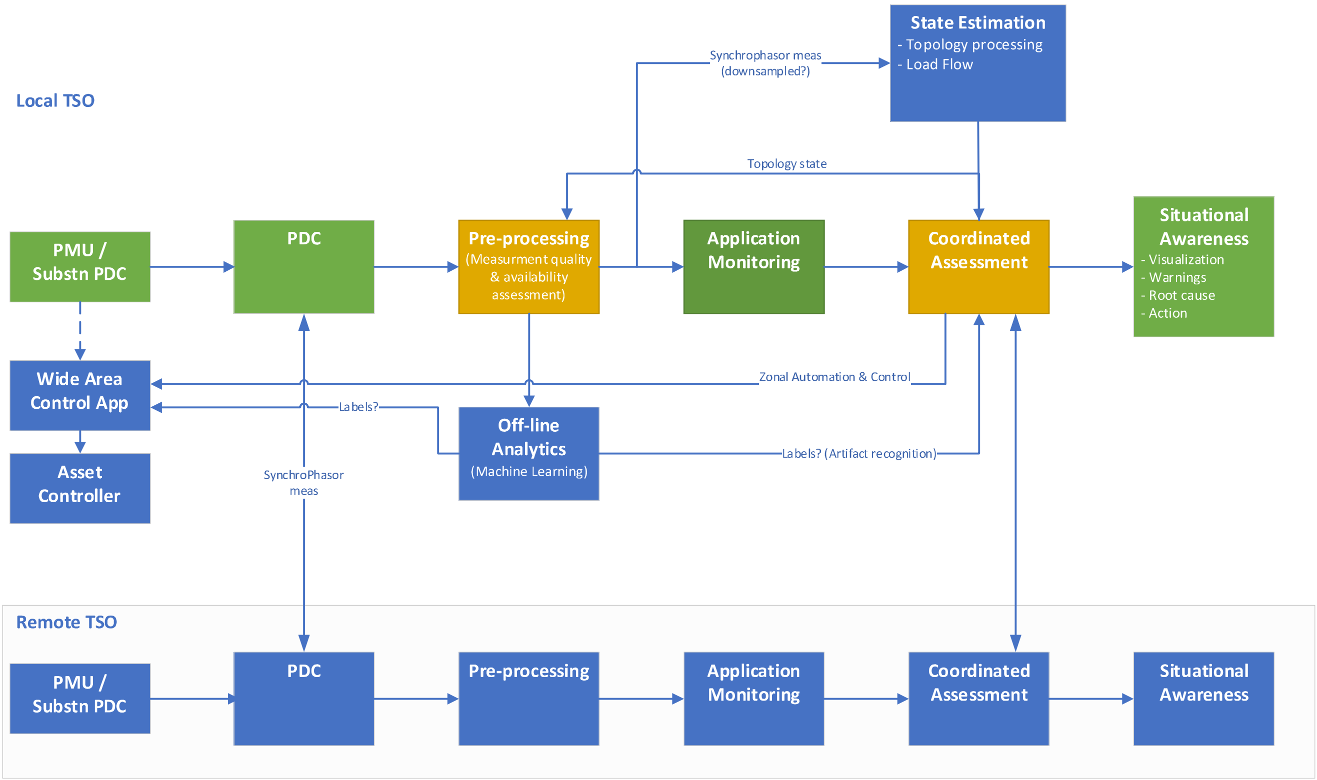

Figure 8: Coordinated Assessment, perspective on Improved WAMPACS/Closed Loop Control

Considerations

The mechanisms for assessing and managing flexible control schemes is complex. The elaborated solutions here are not mature and must be further investigated.

How to model and exchange information between local and distributed applications must be described (information modelling, integration architecture, schema definitions).

The advantages and disadvantages with distributed versus different level of centralised automated control must be further investigated.

How to get effect of AI/ML and data labelling techniques must be further studied.

NEWEPS project results

A flexible integration architecture internally in the local TSO platform are proven effective in the NEWEPS Test & Development platform by using Kafka streams (see chapter 3). It remains to consider how the integration between the TSOs and to the distributed controllers should manifest, however it is recommended to use a consistent information model to achieve flexibility, consistency and integrity for all data exchanged.

The assessment of WAMPAC functionalities have been studied separately in the NEWEPS project, and a WAMPAC application has been implemented in the NEWEPS Test & Demonstration platform, see chapter 5.

2.2.7 Communication Control

In previous sections, the dependency between the quality of the data output from the PMU according to the synchrophasor measurement standard[18] and the quality/usability of a WAMS assessment result is discussed. In section 2.2.5 we discuss how "bad data" may be detected and handled – and to some extent amended.

In addition to measurement artefacts, the WAN communication can introduce artefacts as communication delay (*latency* - e.g. due to long distances and/or lack of optimisation in the communication network), delay variations (*inter-latency*/*jitter* - e.g. due to lack of band-with) and data loss. Such phenomena may affect the WAMS application assessment to various degrees - dependent on the sensitivity of the assessed phenomena.

The PMU standard has no normative reference to such sensitivity, but the technical report IEC 61850-90-5[19] discuss Use Cases (chapter 5) and summarise the communication requirements (chapter 7-4) as follows:

Table 1 Communication Requirements summary.

<table>
<tr><th colspan="2">Factor</th><th>Reporting rate range</th><th>End-to-end Latency*</th><th>Measurement timing error</th><th>Sensitivity to transmission jitter</th><th>Sensitivity to lost packets</th></tr>
<tr><td colspan="2">Sync-check</td><td>≥4/s</td><td>100 ms</td><td>50 μs</td><td>Medium</td><td>High</td></tr>
<tr><td colspan="2">Adaptive relaying</td><td>≥10/s</td><td>50 ms</td><td>50 μs</td><td>Low</td><td>Medium</td></tr>
<tr><td colspan="2">Out-of-step protection</td><td>≥10/s</td><td>50 ms
to 500 ms</td><td>50 μs</td><td>Medium</td><td>Medium</td></tr>
<tr><td colspan="2">Situational awareness</td><td>1/s
to 50/s</td><td>5 s</td><td>50 μs</td><td>Low to medium</td><td>Low to medium</td></tr>
<tr><td colspan="2">State-estimation & security assessment</td><td>1/300s
to 10/s</td><td>5 s</td><td>50 μs</td><td>Low</td><td>Medium</td></tr>
<tr><td colspan="2">Data archiving</td><td>Any</td><td>N/A</td><td>50 μs</td><td>Low</td><td>Medium</td></tr>
<tr><td colspan="2">Wide area controls</td><td>≥10/s</td><td>50 ms
to 500 ms</td><td>50 μs</td><td>Medium</td><td>High</td></tr>
<tr><td colspan="2">Predictive dynamic stability maintaining system</td><td>≥25/s
or 30/s</td><td>50 ms</td><td>50 μs</td><td>Medium</td><td>High</td></tr>
<tr><td colspan="2">Under voltage load shedding</td><td>≥25/s
or 30/s</td><td>100 ms</td><td>50 μs</td><td>Low</td><td>High</td></tr>
<tr><td rowspan="2">Phenomenon assumption type WAMPAC</td><td>PMU to PDC</td><td>1/s
to 10/s</td><td>5 s</td><td>50 μs</td><td>Low to Medium</td><td>Low to Medium</td></tr>
<tr><td>PMU to IED</td><td>50/s
or 60/s</td><td>20 ms</td><td>50 μs</td><td>Medium</td><td>High</td></tr>
</table>

*) Remark! The end-to-end latency (or "application latency") refers to the sum of all delays introduced, both delays in the communication network and in the WAMPACS applications.

[18] Network of correctly functioning PMUs, including their input dependencies (as time synchronisation and metering)

[19] Communication networks and systems for power utility automation – Part 90-5, 2012: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118, Chapter 7-4.

This section addresses how the proposed architecture in the project may utilise commercially available solutions for communication reliability control and coming standards for deterministic asynchronous ethernet communication with high integrity control[20].

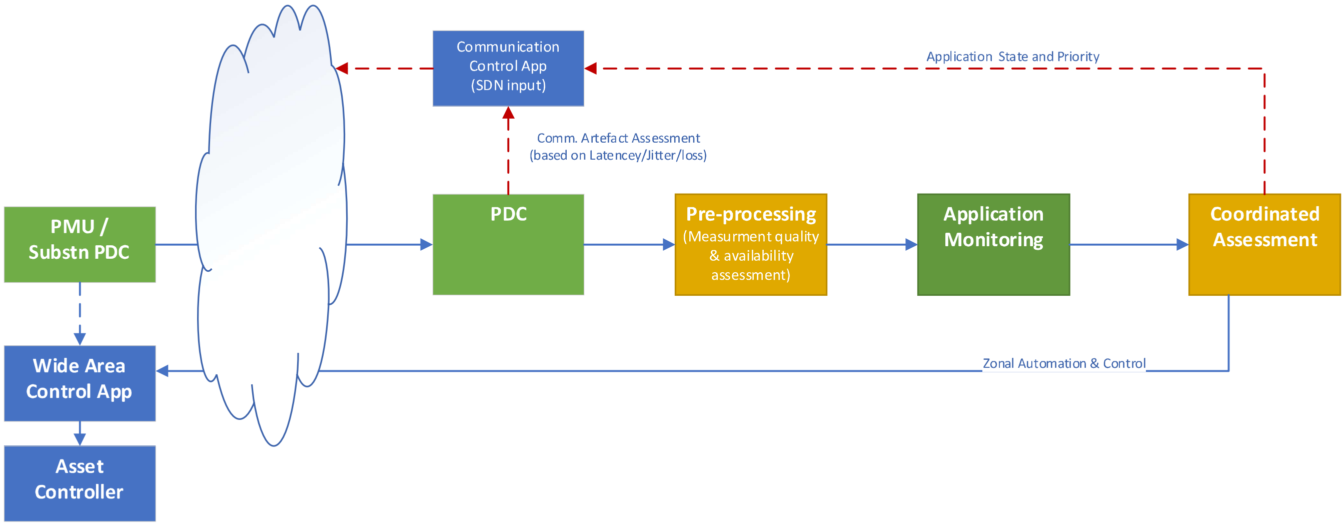

Figure 9: Communication control

Figure 9 shows application components for communication control (measuring latency, jitter and loss variations, and even the capability prioritizing the most critical communication at any time).

The chapter do not address Deterministic LAN aspects in PMU Networks (as e.g. Time Sensitive Networking - IEEE 802.1)

Introduction to resilient/deterministic Wide Area Networking

Considerations is according to

- IEC 61850 Communication networks and systems for power utility automation
  - Part 90-13:2021, Deterministic networking technologies
  - Part 90-12:2020, Wide Area Network engineering guidelines (deterministic networking, Clause A.2)
  - Part 90-5, 2012, Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118 (*Use Cases,* chapter 5 + *Communication Requirements*, *Chapter* 7).

Some Wide Area Networking concepts

SDN (SD-WAN) – Software Defined Networking (SD over Wide Area Networks)

- an approach to computer networking that allows dynamic network administration and configuring network services through software logic.
- The control plane logic makes decisions about traffic flow. The data plane is responsible for forwarding traffic based on this control plane logic.
- The SDN controller is a centralised platform and the "brain" of the SDN network, communicating with network devices (like switches and routers) enabling network automation and orchestration (as e.g.

[20] https://en.wikipedia.org/wiki/Deterministic_Networking, and https://datatracker.ietf.org/wg/detnet/about/

ensuring band with for specific services and dynamically adjusting network traffic flow) and improved security (such as blocking malicious/not known network traffic).

- SD-WAN focused on WAN specifically, - how to efficiently route traffic between remote sites (as Substations) in a Wide Area Network and centralised resources (as Control Centres). It optimises the management of WANs e.g. by dynamically selecting the best path for network traffic based on factors like bandwidth, latency, etc. ensuring better performance, and providing enhanced security, reliability, and scalability.

MPLS – Multiprotocol Label Switching

- a networking technology that routes traffic using the shortest path based on "labels," rather than network addresses, to handle forwarding over private wide area networks.
- data packets are assigned labels by the Ingress Router (the router that first receives the data). These labels can be used by Label Switch Routers (LSRs) to forward the packet along a pre-determined path (a Label Switched Path, LSP), to the Egress Router (the router at the destination). MPLS allows the creation of Explicit routes for specific traffic flows, making it possible to avoid network congestion, optimise path utilisation, and ensure that certain nodes or types of traffic (as Synchrophasor data) receive preferential treatment.
- While MPLS can prioritise traffic, it doesn't dynamically adapt to changing network conditions, such as congestion, latency, or packet loss. SDN can optimise MPLS networks in a variety of ways:
  - *Enhanced Quality of Service (QoS) Management*

    While MPLS offers some QoS features, the implementation can be rigid, and the priorities are predefined. The SDN controller can adjust traffic priorities dynamically based on real-time application requirements and network conditions. For example, if a prioritised synchrophasors channel becomes congested, SDN can increase its priority on MPLS paths e.g. to ensure low latency.
  - *Policy-Based Automation*

    The SDN controller can automatically enforce policies across the network, ensuring that MPLS traffic is routed and managed according to the WAMPAC system's needs. Policies can be adjusted in real-time without requiring manual intervention.
  - *Centralised Traffic Control and Path Optimisation*

    An SDN controller has global network visibility and may automate the network to reroute traffic over the best available paths, reducing latency and congestion, e.g. based on performance metrics.
  - *Dynamic Traffic Engineering*

    Traditional MPLS provides traffic engineering capabilities to define explicit paths for specific traffic types, though the traffic engineering rules are typically static and must be manually configured by network operators. The SDN controller can automatically reroute MPLS traffic based on network conditions in real-time, making traffic management more agile and responsive (e.g. by adjusting the MPLS LSPs to avoid congestion or balance traffic across multiple paths to maximise resource utilisation.
  - *Network Resiliency and Failover*

    MPLS offers resiliency features like *Fast Reroute* (FRR) and *Path Protection,* but traffic may experience downtime/packet loss if a router fails, and it reroutes to backup paths. With SDN the traffic can automatically reroute to the most optimal path based.
  - *Network Visibility and Monitoring*

    MPLS provides limited visibility into network performance from the user's perspective (e.g., application performance, latency, packet loss). To monitor MPLS networks, operators often must rely on separate network management tools, which may not provide a complete picture of the entire network's health. The SDN controller continuously collects and analyses network performance metrics in real-time, allowing operators to monitor the health of MPLS circuits and optimise performance based on the collected data.

LDP – Label Distribution Protocol (and *label-switched path LSP*)

- a protocol that automatically generates and exchanges labels between routers (keeps trace of neighbours and exchanges labels used to build and maintain label-switched path (LSP) databases that are used to forward traffic through MPLS networks,
- a protocol that automatically generates and exchanges labels between Label switched Routers to establish Label Switched Paths (LSPs) across an MPLS network. LDP is responsible for distributing labels so that the routers can forward traffic based on labels attached to the data packets (rather than performing IP routing),
- LDP is used in conjunction with Interior Gateway Protocols (like OSPF) to calculate the optimal paths for LSPs. Once the path is determined, LDP labels are announced to each hop establishing a mapping (label binding) which indicates which particular route or group of routes a label is used for.
- SRv6 (Segment routing with IPv6) offers an even more powerful mechanism for applications to control how their traffic is routed through the network, taking advantage of the programmability, flexibility, and efficiency of IPv6.
  - As SRv6uses the IPv6 addresses to represent the segments - and the segment information is encoded in the Segment Routing Header (SRH) of the IP packet, it gives even more flexibility than MPLS-SR and allows more fine-grained traffic engineering and path control as it can encode complex paths or even specific network services in the segment list.
  - By leveraging SRv6, applications can gain fine-grained control over how their data is transmitted across the network, taking advantage of its flexibility, scalability, and programmability to meet strict performance, reliability, and security requirements.
- As SRv6 (*Segment routing with IPv6*) uses the IPv6 addresses to represent the segments - and the segment information is encoded in the *Segment Routing* Header (SRH) of the IP packet, it gives even more flexibility than MPLS-SR, as
  - SRv6 allows more fine-grained traffic engineering and path control as it can encode complex paths or even specific network services (like firewall or load balancing) in the segment list.
  - The routers along the path process the SRH and perform the actions specified by the addresses in the list.
  - The segments can include addresses that represent nodes, links, or even network functions (e.g., load balancing or firewall operations).
  - SRv6 allows for centralised path computation via an SDN controller. This simplifies path computation and network management by using IPv6 addresses, which can be easily manipulated for complex traffic engineering and network slicing.

SR – Segment Routing

- SR is an architecture that seeks the right balance between distributed intelligence and centralised optimisation. It is tightly aligned with SDN principles, especially in terms of centralisation, programmability, and flexibility in network control.

- SR provides complete control over the forwarding paths by combining simple network instructions (segment list). It does not require any path signalling. Hence, per-flow state only needs to be maintained at the ingress node of the Segment Routing domain increasing network flexibility.
- SR is highly programmable, e.g. for fine-grained control over the forwarding path. With SDN, this capability can be extended to the entire network, where application-driven policies can be implemented. For instance, an application could request low-latency paths, or high-bandwidth paths for video traffic, which the SDN controller can configure using Segment Routing.
- SR runs natively on an MPLS or IPv6 data plane. A simple software upgrade will enable your hardware to run it. SR can coexist with existing LDP network.
- Segment Routing with MPLS (SR-MPLS) operates similarly to traditional MPLS in terms of label switching but differs in the way the labels are distributed and managed. SR-MPLS provides a simple yet powerful way to control the path traffic takes, using a combination of node and adjacency segments. This enables path optimisation for specific applications or traffic classes.
- SR-MPLS combines the simplicity and flexibility of Segment Routing with the MPLS forwarding paradigm (using of MPLS as the transport mechanism for the segments).

Scalability and Simplified Network Management:

- By using Segment Routing in conjunction with SDN, operators can significantly simplify network management. The SDN controller can automatically calculate and assign paths (segments) across the network, eliminating the need for manual configuration and complex signalling protocols (e.g., RSVP-TE).

Flexibility and Dynamic Traffic Engineering:

- SR enables more flexible traffic engineering than traditional MPLS because the source node defines the path. With SDN, operators can dynamically adjust traffic paths based on real-time network conditions, offering better network resource utilisation and traffic optimisation.

Improved Network Efficiency:

- Combining Segment Routing with SDN and MPLS helps improve overall network performance by enabling efficient path selection based on network state and application needs. The ability to bypass congested or underperforming links and direct traffic over the best available path leads to better network performance.

Reduced Operational Complexity:

- By removing the need for label distribution protocols (LDP, RSVP-TE), SR reduces operational complexity, making it easier to deploy and maintain the network. The SDN controller can automate path programming and label distribution, leading to reduced errors and faster time to service.

IETF-DetNet (Deterministic networking)

- DetNet is a Deterministic networking protocol standard under development by Internet Engineering Task Force, ensures predictable, reliable, and low-latency delivery of data across networks, especially for applications that require strict performance guarantees, such as industrial automation, mission-critical communications, time-sensitive networking (TSN), and 5G networks. The Key Goals are:

  Deterministic Data Delivery:

  - The primary goal is to enable deterministic behaviour in packet-switched networks, meaning that data transmission can be precisely controlled and timed to meet strict requirements such as latency, jitter, and packet loss.

Support for Mission-Critical Applications:

- DetNet is designed to support applications where reliability, low latency, and predictability are paramount. This includes use cases such as IoT, smart grids, autonomous vehicles, factory automation, and audio/video streaming.

Traffic Engineering:

- The working group is focused on protocols that allow for traffic engineering to ensure that the right paths and resources are allocated to meet deterministic requirements, including bandwidth reservations and priority handling of critical traffic.

Seamless Integration with Existing Networks:

- The goal is to achieve deterministic performance while integrating into existing IP-based networks, allowing for backward compatibility with traditional best-effort traffic while reserving resources for critical flows.

Low-Latency, High-Reliability Paths:

- DetNet aims to ensure low-latency and high-reliability paths for time-sensitive traffic, through mechanisms like flow aggregation, traffic classification, and path protection.

Hypotheses

Though commercially available technologies are rapidly emerging, it is mature enough to gradually implement most deterministic mechanisms in real-time PMU networking in a Nordic WAMPAC system – ensuring low latency, jitter and data loss.

With the new SDN/SR automation Capabilities the application will play an important role in automated controlling and orchestrating the determinism in the wide area communication network for WAMPAC.

Considerations

Within the defined measurement quality limits given by IEEE c37.118.1[21], the estimated synchrophasor measurement input to WAMS applications and, for WAMPAC, the control action output from the control system must be communicated with high integrity and determinism. The requirements should be agreed.

TSO should have unified functional requirements, but as the maturity over time may differ in their WAN architecture (MPLS, SDN/SD-WAN, different Segment Routing capabilities, etc) the implementation may be different. A unified design supporting SDN capabilities should however be implemented in the common Nordic inter-TSO WAN network (*Electronic Highway* - EH) to ensure both integrity and determinism.

To measure WAN communication artifacts either the in-built SDN monitoring mechanisms may be used for determining latency, jitter, and loss, or let the WAMPAC application monitor end to end latency.

NEWEPS project results

No deterministic capability is implemented or tested in the NEWEPS project, but parallel communication development is ongoing at the TSOs enabling such capabilities.

[21] IEEE c37.118.1 (2011) + Amendment 1 (2014) *Standard for Synchrophasor Measurements for Power Systems*, chapter 5 *Synchrophasor measurement requirements and compliance verification*.

2.2.8 Practical example: Component Virtualisation & Integration

Figure 10 shows an exemplified manifestation of the architecture considerations described, with

- The basic components for PMU networking and SCADA/EMS.
- Integration environment (Kafka / Kafka streams and some proposed adapters).
- WAMPAC computing (containerised micro service environment) for real-time analytics.
- Data base for time series archiving.
- Off-line analytics environment for machine learning, application development, tuning, etc.

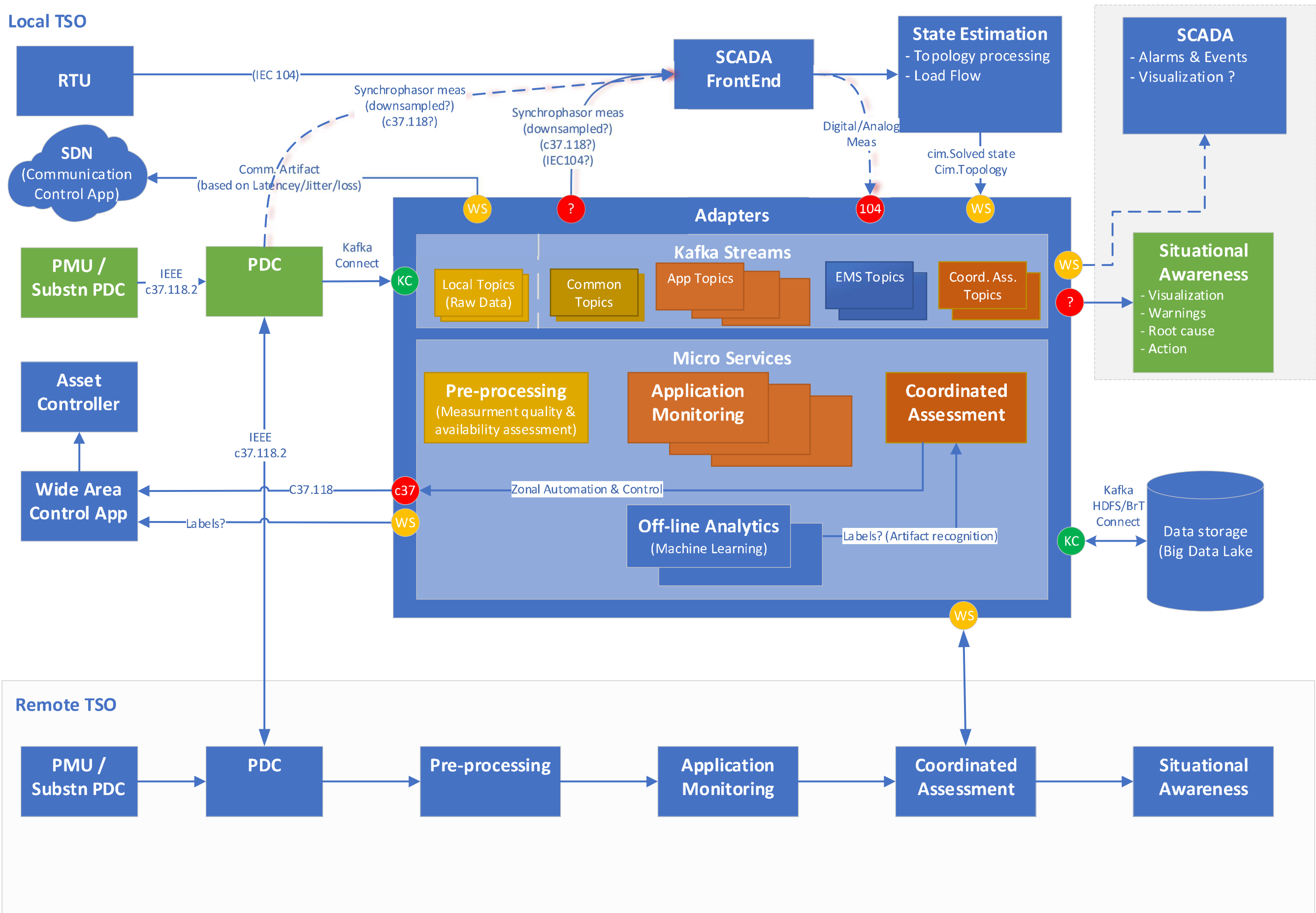

Figure 10: Practical example: Component Virtualisation & Integration

2.3 Data quality perspectives

2.3.1 Background

In the context of power oscillations and voltage stability monitoring, the modern data-sharing architecture is in principle twofold, consisting of: SCADA and WAMS.

SCADA system provides centralised monitoring based on Remote Terminal Units (RTU) and Intelligent Electronic Devices (IED) in substations, which provide access to measurements, breaker status and alarms. The data is collected at a central SCADA server, which commonly polls the local devices (RTUs and/or IEDs) cyclically using a master-slave approach every 2-30 seconds. Alternatively, event-based data collection can also be used, where data is communicated from the substation when a change exceeding a certain threshold has occurred. The feasibility of an event-based approach is restricted by the communication network, which can be overloaded during significant disturbances if its capacity is under dimensioned.

WAMS is built on two main components: Phasor Measurement Units (PMU) which processes measurements locally in substations, and Phasor Data Concentrators (PDC) which aggregates the values from several PMUs at a central location. The base measurements are time-synchronised voltage and frequency measurements. However, it can also include current phasor measurements and rate of change of frequency (RoCoF). Common reporting rates are specified in the C37.118 standard. WAMS does not use the master-slave approach of the SCADA system and is more sensitive to data loss and delays. However, in contrast to SCADA, WAMS normally do not provide any information about breaker status, alarms, or other functionality, which is inherent to why WAMS was created originally (monitoring oscillations and voltage).

These two systems are therefore interdependent to achieve the highest possible observability. Between different TSOs or other actors, the Inter-Control Center Communications Protocol (ICCP)[22] can be used for SCADA related data. ICCP is based on a client/server paradigm, so TSOs subscribe to chosen datasets, which can be available both on a cyclic basis or unprompted. For WAMS system, the C37.118-2 standard or IEC 61850 specifies protocols for communication between PDCs of different TSOs.

2.3.2 System models for Data Quality studies

Based on the SCADA and WAMS delimitations and requirements, three probable future architectures for integration of the system families have been proposed by ENTSO-E[22]. These are summarised below and have been used as a reference for the system models used in the data quality studies presented in this section.

In the architectural figures: CFE is the SCADA communications front end, and PDC is the Phasor Data Concentrator. Area one and Area two represent two different TSO control areas. Time delays, denoted t_L and t_{proc}, refer to the delays in each communication and processing step.

1. **Architecture one:** Separate WAMS and SCADA: This is the current state-of-the-art WAMS, presented in Figure 11. Each TSO has their own separate WAMS and SCADA system. Therefore, each actor and area are independent in their data rates and requirements, even if central standards exist.

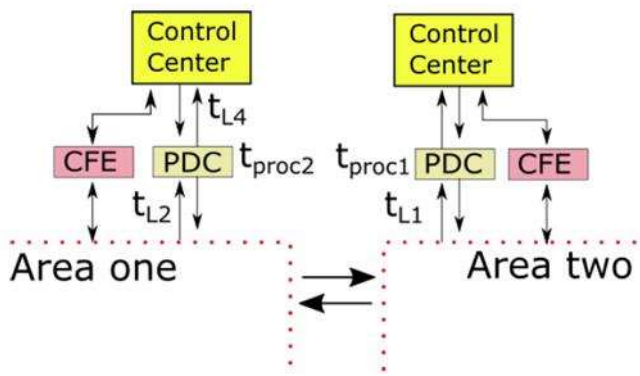

Figure 11: Architecture one with separate WAMS and SCADA platforms, from [23]

[22] ENTSO-E Wide Area Monitoring Systems State of Play and Future of Data Exchange report from RDIC WG5

[23] A. ter Vehn and L. Nordström, *Estimating unobservable machines in multi-area power systems considering model imperfections*, IEEE PowerTech, Belgrade, 2023

2. **Architecture two**: WAMS super PDC and separate SCADA: A common data-sharing architecture where data is shared easily amongst actors, using a central PDC. The setup is visualised in Figure 12. The super PDC is interfaced with all other PDCs and is available to all actors connected to it. Observability is maximised in terms of measurements, while the communication latency increases.

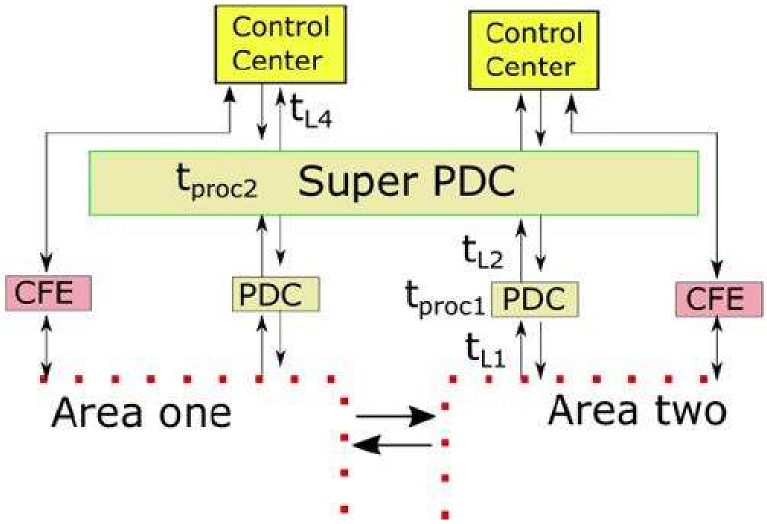

Figure 12: Architecture with common WAMS super PDC and separate SCADA, from [23]

3. **Architecture three**: Central platform (WAMS and SCADA): This architecture combines the SCADA and WAMS system of all actors across a synchronous region, as in Figure 13. Organisational boundaries do not exist in this configuration and one centralised chosen application is used.

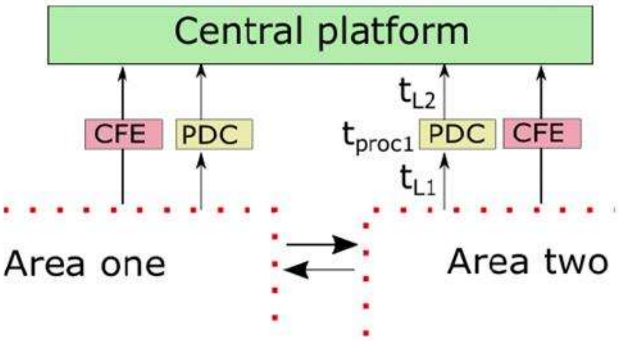

Figure 13: Architecture with central WAMS and SCADA platform, from [23]

2.3.3 Data-sharing architectures vulnerability and quality issues

Due to general vulnerabilities which exist in any communication system, SCADA and WAMS may be subject to problems such as congestion, disturbances, latency, failure to retrieve data, measurement errors and more. The reason for these errors is defined by the system configuration, such as how accurate the measurement devices are, how many devices are available but also human intervention – such as simple mistakes during maintenance or cyberattacks. The consequences of the aforementioned issues can be viewed as loss of data, faulty data, delayed data which in turn can lead to incorrect assumptions of the system state, to faulty inputs to essential system applications. The importance of this cannot be overstated, as the data is usually assumed to be correct by the end user, while it's used from everything from contingency planning to evaluating market prices and making control decisions – both on a human level and on an application level. In short, data quality must be guaranteed to ensure correct system performance. Therefore, multiple system applications have been developed to improve data quality, where the method also detects and minimise the consequences of measurement errors. The one investigated in this project is state estimation.

2.3.4 Methods for Data Quality improvement investigated

As previously mentioned, the WAMS is an essential data-sharing architecture for dynamic analysis when analysing for instance, power oscillations. However, it is rare that PMUs exist for every single transmission line and cable available to the grid owner. To achieve full system understanding, it is common to apply methods in the area of state estimation. State estimation uses known physical relations described as mathematical models, along with available measurements, to derive the states which are unknown. Furthermore, the method also minimises measurement errors, through correcting measurements based on known electrophysical laws such as Kirchhoff's laws of currents and voltages.[24]

State estimation in a power system context exists in three categories shown in the figure below; Static state estimation, Forecasted aided state estimation and Dynamic state estimation, used for static to dynamic application areas. In the NEWEPS project, the focus has been on Dynamic state estimation for the purposes of enabling voltage and power oscillation application.

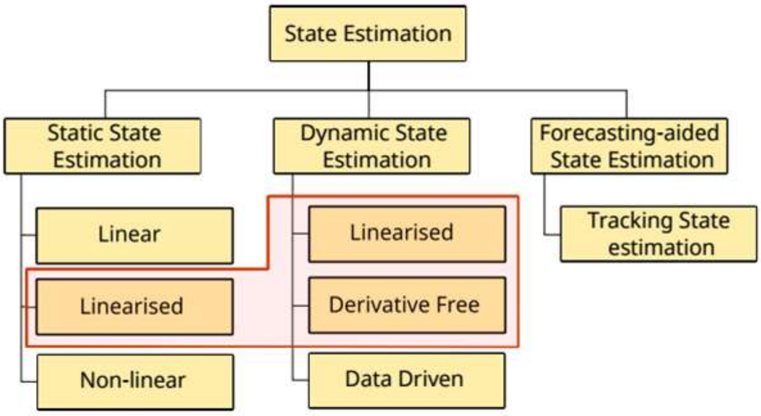

Figure 14: Overview of state estimation categories

Dynamic estimation through Kalman filtering is a common approach with multiple different variants[25]. The one investigated in the project is the Extended Kalman Filter (EKF) and UKF,[26] . The Kalman filters use a dynamic model along with differential equations to estimate the next timestep of the system, which is then used in comparison with the actual measurements. It achieves this by assigning a standard deviation to each state, which defines the certainty of the state. As the measurements also have a certain standard deviation based on the inherent errors, these can be used for comparison to correct the state. The EKF uses a linearised model while UKF uses an unscented transformation.

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[24] Abur, A., Gomez-Exposito, A.; *Power System State Estimation: Theory and Implementation*, Taylor-Francis, ISBN 978-0824755706

[25] Simon D., *Optimal State Estimation: Kalman, H∞, and Nonlinear Approaches*, John Wiley & Sons, ISBN 9780471708582

[26] C. Muscas, P. A. Pegoraro, S. Sulis, M. Pau, F. Ponci, and A. Monti, *New Kalman filter approach exploiting frequency knowledge for accurate pmu-based power system state estimation*, IEEE Transactions on Instrumentation and Measurement, vol. 69, no. 9, pp. 6713–6722, 2020

EKF process[27]

The EKF is an extension of the Kalman filter and is mainly used for non-linear problems. As power system dynamics are non-linear, this approach is therefore suitable. The non-linear system dynamics are commonly represented as follows

$$x_{k+1} = f(x_k, u_k, t_k) + w_k$$
$$y_k = h(x_k, u_k, t_k) + v_k$$
$$w_k \sim N(0, Q_k)$$
$$v_k \sim N(0, R_k)$$

where $f(x_k, u_k, t_k)$ is the non-linear propagation function, $h(x_k, u_k, t_k)$ is the non-linear measurement function and w_k and v_k are assumed to be Average White Gaussian Noise (AWGN) as follows

$$p(w_k) \sim N(0, Q_k)$$
$$p(v_k) \sim N(0, R_k)$$

For the EKF, the differential function and the measurement function are linearised based on the current state

$$A_k = \frac{\partial f_k}{\partial_x}\Big|\hat{x}_k \quad H_k = \frac{\partial h_k}{\partial_x}\Big|\hat{x}_k$$

Which are then used to propagate the state as follows

$$\hat{x}_k^- = A_{k-1}\hat{x}_{k-1}$$
$$P_k^- = A_{k-1}P_{k-1}A_{k-1}^T + Q_{K-1}$$
$$K_k = P_k^- H_{k-1}^T (H_{k-1}P_k^- H_{k-1}^T + R_{k-1})^{-1}$$
$$\hat{x}_k = \hat{x}_k^- + K_k(y - h(\hat{x}_k^-, u_k, t_k))$$
$$P_k = (1 - K_k H_k)P_k^-$$

Where P_k is the state covariance matrix, Q_k is the process noise matrix while R_k is the measurement noise matrix.

UKF process[27]

The UKF method was created to address the limitations with linearisation and providing a more reliable way to approximate mean and covariance. It does so through the unscented transformation, which works by producing a set of points x(i) (i = 1, 2, ..., 2n + 1), referred to as sigma-points, so that through an arbitrary non-linear function $y^{(i)} = g(x^{(i)})$, the mean $\bar{y}$ and covariance P_y will approximate the a posteriori state and covariance. The dynamics remain the same, and if we apply this methodology to the non-linear functions, we obtain:

$$\hat{x}_{k+1}^{(i)} = f(\hat{x}_k^{(i)}, u_k, t_k)$$
$$\hat{x}_{k+1}^- = \sum_{i=1}^{2n} W_{(i)}^m \hat{x}_{k+1}^{(i)}$$
$$P_x^- = \sum_{i=1}^{p} W_{(i)}^c \left(\hat{x}_{k+1}^{(i)} - \hat{x}_{k+1}^-\right)\left(\hat{x}_{k+1}^{(i)} - \hat{x}_{k+1}^-\right) + Q_k$$

where $W_{(i)}^m$ and $W_{(i)}^c$ are associated weights, where

[27] A. ter Vehn and L. Nordström, *Dynamic state estimation considering topology and observability in multi-area systems*, IEEE PES ISGT EUROPE 2023, 2023, pp. 01–05

$$\sum_{i=1}^{2n} W_{(i)}^{c} = \sum_{i=1}^{2n} W_{(i)}^{m} = 1$$

and Q_k is the process noise. As for the sigma points, each point of $x^{(i)}$ is generated using the covariance P_k of $\hat{x}_k$, such that:

$$\hat{x}_k^{(i)} = \hat{x}_k + \tilde{x}^{(i)} \qquad i = 1, \dots, 2n$$

$$\tilde{x}^{(i)} = (\sqrt{(n+\lambda)P_k})_i^T \qquad i = 1, \dots, n$$

$$\tilde{x}^{(n+i)} = -(\sqrt{(n+\lambda)P_k})_i^T \qquad i = 1, \dots, n$$

where λ is defined from[28] and equal to $\lambda = \alpha^2(1-n)$ for the context of this report. The weights are also defined as in[28], where α = 0.1 and β = 2. With the covariance and a priori covariance known, we can use the measurement function to estimate the measurements as follows:

$$\hat{y}_{k+1}^{(i)} = h\left(\hat{x}_{k+1}^{(i)}, t_{k+1}\right)$$

$$\hat{y}_{k+1} = \sum_{1=1}^{2n} W_{(i)}^{m} \hat{y}_{k+1}^{(i)}$$

We can also deduce the covariance for the measurements and between the measurements and the states through

$$P_y = \sum_{i=1}^{p} W_{(i)}^{c} (\hat{y}_{k+1}^{(i)} - \hat{y}_{k+1})(\hat{y}_{k+1}^{(i)} - \hat{y}_{k+1}) + R_k$$

$$P_{xy} = \sum_{i=1}^{p} W_{(i)}^{c} (\hat{x}_{k+1}^{(i)} - \hat{x}_{k+1}^{-})(\hat{y}_{k+1}^{(i)} - \hat{y}_{k+1})$$

Using the aforementioned equations, we find that the mean and the covariance is preserved through the non-linear transformation. Thereby, all sigma-based equivalents for the Kalman filter are as follows

$$K_{k+1} = P_{xy} P_y^{-1}$$

$$\hat{x}_{k+1} = \hat{x}_{k+1}^{-} + K_{k+1}(y_{k+1} - \hat{y}_{k+1})$$

$$P_{k+1} = P_{k+1}^{-} - K_{k+1} P_y K_{k+1}^T$$

In the context of power systems, the states commonly used are the voltage magnitude and voltage phase. The limiting factor however in power systems is that because electricity moves at light speed, there has previously been very difficult to create a dynamic model used for estimation. This in combination with a lack of PMUs make it difficult to assess the entire grid state dynamically. In the NEWEPS Test & Demonstration platform, we have investigated the sensitivity in[29] and found that while delays and measurement errors can be processed, a lack of measurements, incorrect assessment of system state and significant disturbances make the estimation quality degrade. This can be observed in Figure 15, which are estimation results for simulations on the Nordic-44 system. Here, a test setup was created where a power system simulator (PowerFactory) was connected to an external estimation setup, with an emulated data-sharing SCADA and WAMS interface.

[28] E. Wan and R. Van Der Merwe, *The unscented kalman filter for nonlinear estimation*, IEEE 2000 Adaptive Systems for Signal Processing, Communications, and Control Symposium (Cat. No.00EX373), 2000, pp. 153–158.

[29] ENTSO-E Wide Area Monitoring Systems State of Play and Future of Data Exchange report from RDIC WG5

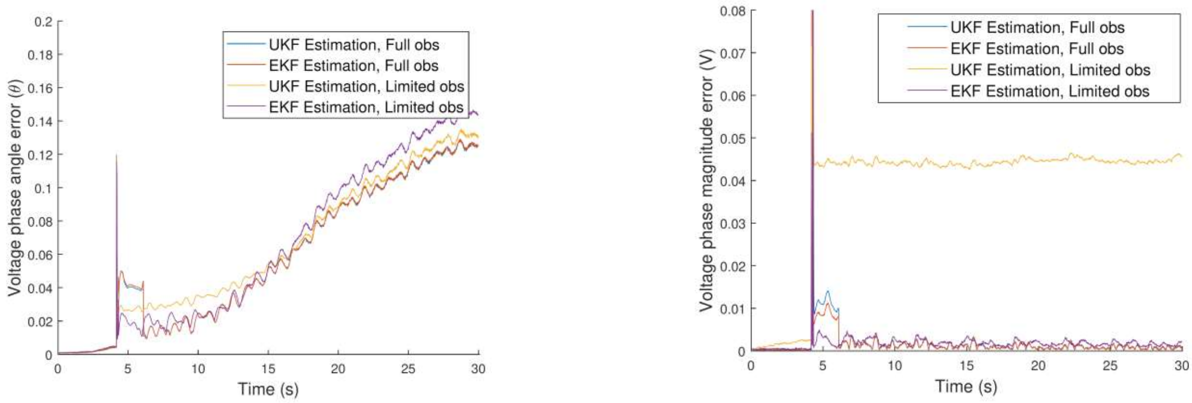

Figure 15: Simulations results on the Nordic-44 system, with full or limited observability during a short circuit fault disturbance, from [30].

Using these findings and the modification proposed in [30], where frequency was included as a state, the change of the phases could be predicted with high accuracy. However, this still left an issue of magnitude estimation. Through the inclusion of SCADA data for buses, including voltage and power measurement where PMU measurements are unavailable, observability for these missing data points could be corrected. This caused a dramatic improvement in dynamic estimation quality. In [31], the approach was tested both for the simulation environment and with real data from the Nordic WAMS/SCADA systems for a small part of the network, which are shown in Figure 17 and Figure 18. Furthermore, the method was applied for a great disturbance in the Nordic grid, as can be seen in Figure 19.

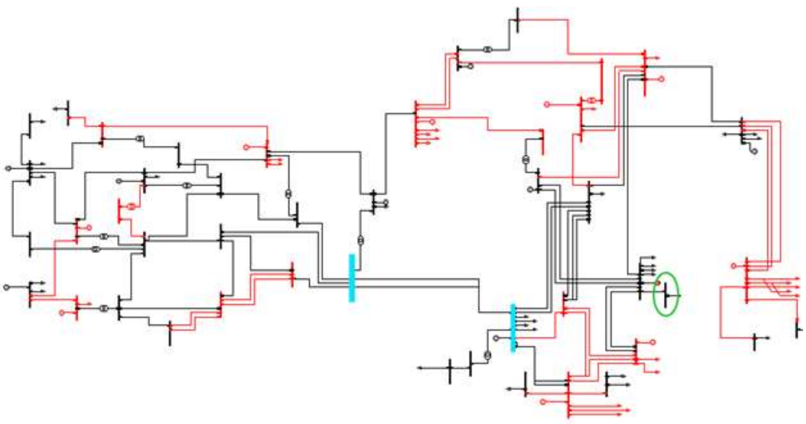

Figure 16: Nordic-44 grid model in PowerFactory, used for simulation studies of state estimation.

[30] A. ter Vehn and L. Nordström, *Dynamic state estimation considering topology and observability in multi-area systems*, IEEE PES ISGT EUROPE 2023, 2023, pp. 01–05

[31] A. ter Vehn, L. Nordström and S. Apelfröjd, *Performance Evaluation of Hybrid State Estimation Using Real TSO Data Sources*, IEEE PMAPS New Zealand 2024, 2024, pp. 01-05

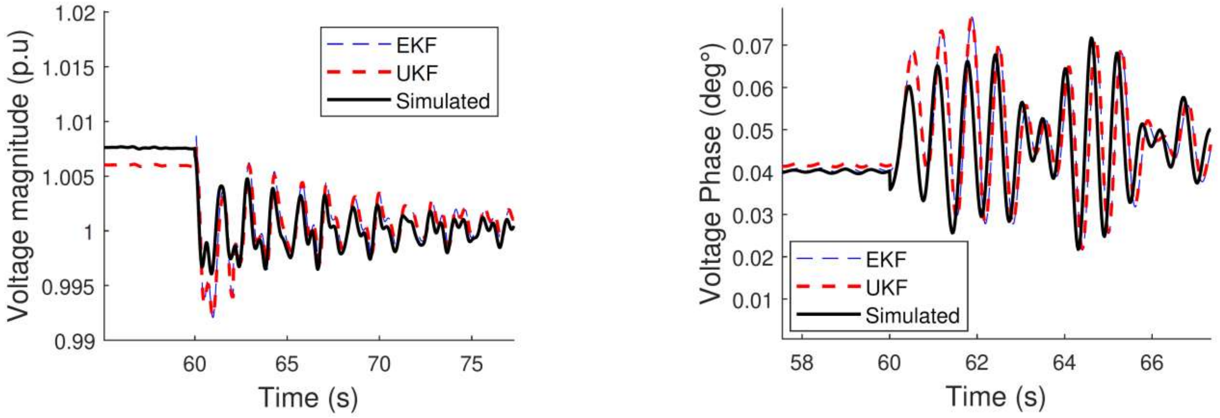

Figure 17: Simulations results on the Nordic-44 system, with modified hybrid dynamic estimation approach and limited observability during a short circuit fault disturbance, from [31].

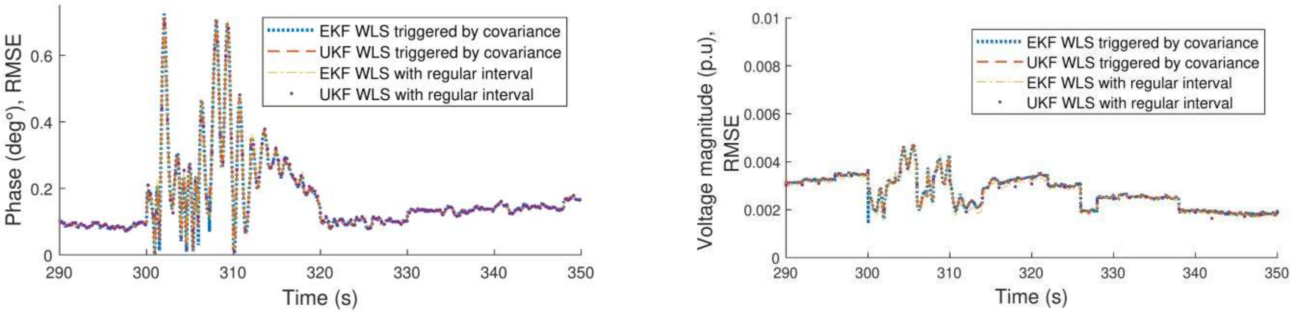

Figure 18: Root mean square error of hybrid dynamic state estimation. Test was performed with real transmission system data and model with limited observability, from [31].

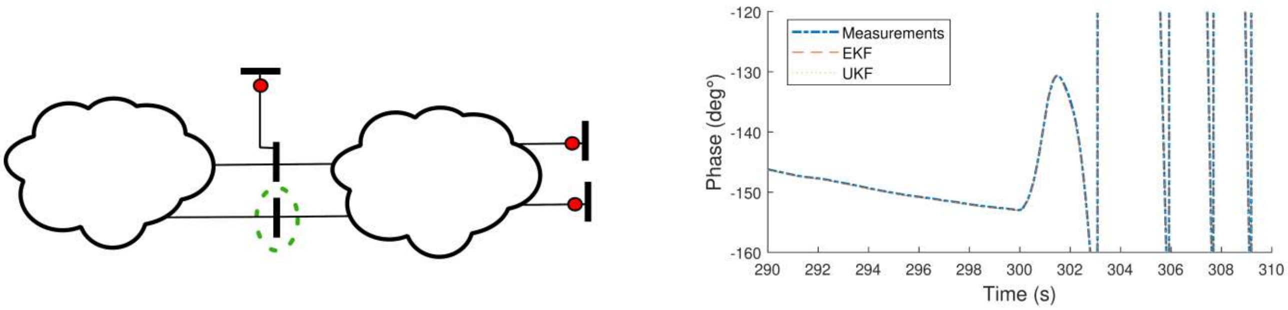

Figure 19: Left: Real TSO model used for case study, where green dashed circle marks a spot with a PMU which is used for verification purposes and not during estimation. Right: Figure shows estimation results at the bus encircled by the dashed green circle, during a real disturbance, from [31].

2.4 Visualisations perspectives: human – system collaboration

2.4.1 Introduction

Today's WAMS and WAMPAC systems support TSOs by:

1. Creating situational awareness,
2. Providing decision support for implementing countermeasures, and

3. Automating tasks using real-time PMU data[32].

A survey of ENTSO-E members[33] shows that the main trends in the use of WAMS and WAMPAC systems today are the following:

- **Offline analysis** (in 35% of cases) focusing on actual events and improving and validating dynamic models.
- **Real-time monitoring** (in 33% of cases) focusing on data and alarm triggers serving to improve the "general situational awareness to verify the system is and remains in normal system state" and to "provide critical information to support remedial actions and restoration processes" (ibid).

The primary focus of contemporary WAMS systems is to visualise critical dynamic parameters of the electric grid, for example, power oscillations, frequency instability, voltage instability, damping status, etc.[33] However, conventional visualisation approaches are impacted by two interrelated trends:

- A rapid advancement and development in the field of data analysis, machine learning and artificial intelligence (AI).
- Machine learning and AI allow rapid analysis of large volumes of data (e.g., PMU data) and can enable more advanced digital services such as digital assistants.

These trends present new perspectives and opportunities in decision support for TSOs. For instance, future systems could incorporate better data analysis systems, including AI subsystems, dedicated to processing and analysing vast amounts of historical and real-time PMU data. With this data, the systems could monitor in real-time for early signs of power oscillations, voltage instability, and other problems, explain the causes of critical events, and propose potential scenarios for development and preventive actions to be taken.

The implementation of novel data analysis methods introduces new requirements for interaction design. The novel aspect in the present work lies in the effort to create an interface that contributes to effective collaboration between humans and the technical system, with each playing a crucial role. The design principles were focused on enhancing human-system collaboration and decision-making. The following key design principles and assumptions were applied:

- **Human-system collaboration**: The envisioned future WAMS/WAMPAC system could operate automatically, semi-automatically, or manually. However, in the present work, operators are expected to remain actively involved in the decision-making process for the foreseeable future, ensuring that human expertise, understanding and responsibility plays a key role.
- **Transparency**: Advanced models and systems should not be perceived as "black boxes". Transparency may be essential for building trust. It is assumed that operators need to understand the reasoning behind system recommendations, actions, and solutions to enhance situational awareness and allow for human input, based on experience and understanding of the situation.
- **Task allocation**: Clear role definition for both humans and systems may be essential to avoid confusion and misunderstandings. The solution should use both technical and human strengths. In this work, technical systems are expected to provide rapid, data-driven analysis and predictions to support proactive decision-making.

[32] M. Maheswari, N. Suthanthira Vanitha, N. Loganathan, *Wide-area measurement systems and phasor measurement units*, (Chapter in Power Systems (POWSYS), Springer Link, pp. 105-126, 2020)

[33] ENTSO-E, "WAMS – state of play and future of data exchange", (ENTSO-E, Tech. Rep., 2021)

- **Proactive rather than reactive response**: Events in the power grid can escalate so quickly that operators might not have time to thoroughly analyse the situation. In such cases, real-time, data-driven systems, together with model-driven automated applications, can offer rapid analysis and predictions, providing early warnings and enabling preventive action before problems escalate.
- **Ergonomic interaction model**: The interface should facilitate easy, intuitive information exchange between the system and the user. By integrating data more effectively, the user interface can offer consolidated, ergonomic visualisations, reducing the need to switch between multiple systems and screens.

2.4.2 Methodology

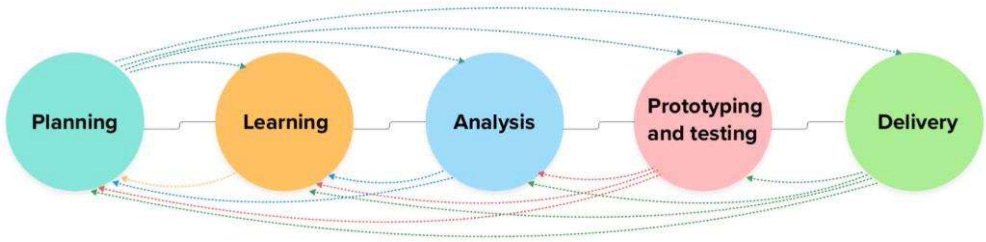

Figure 20: Iterative service design principle.

The development of the visualisation concept was based on the principle of iterative service design. This approach implies the design process as a continuous process based on planning the process and activities, learning, analysis, prototype development, testing, and refining in response to user needs as a final project delivery (see Figure 20). A more detailed description of the activities carried out within each stage is provided in Table 2.

Table 2 Iterative service design through all project stages.

Stage	Description	Activities	Common for all stages
Planning	Planning of the project activities	Planning of activities to focus on	- Continuous dialogue with TSOs and project participants - Continuous thinking of prototype functionalities and priorities based on TSOs needs
Learning	Understanding the actual needs of TSOs	Performing a State-of-the-Art study in relation to WAMS / WAMPAC systems, workshops, and interviews with TSOs, project participants, and area experts	
Analysis	Analysis of needs and insights received in different ways	Performing analysis of data, using this data as a background for a prototype development	
Prototyping and testing	Developing, testing, and validating the design concept	Prototype testing, its validation with TSOs, and refining based on their feedback	
Delivery	Finalising the delivery and final steps	Producing final deliverables (prototype, article, final report)	

2.4.3 Learning

In order to develop and design appropriate visualisation concepts, it is essential to have a good understanding of user needs. This involved an exploration of user journeys of the Norwegian and Swedish TSOs, mapping out their needs and experiences step by step. The work started with an initial workshop, where TSO representatives were asked to describe their vision of how a future WAMS/WAMPAC system should handle voltage instability. They were also asked to describe a typical action scenario used by the operators when voltage instability occurs.

Discussions with Statnett and Svenska kraftnät about the TSOs' needs, insights from their work processes, and relevant approaches to visualisation continued throughout the project. The TSOs and other NEWEPS project participants iteratively provided feedback on the evolving visualisation concept during project meetings. In addition, three representatives from the Islandic TSO (Landsnet) and an area expert from RISE were interviewed. They were also asked to provide their feedback on the visualisation concept.

It also needs to be mentioned that this work relies on background and concept design from the research project ASAP[34].

2.4.4 Analysis

Summarising the insights gained from the TSOs, the following general needs were identified:

- To avoid problems and to remain within safe operational boundaries.
- To get an indication of when and where in the grid a problem starts.
- To gain a better understanding of the operational status and potential sources of problem in the area.
- To understand what tools are available to resolve the problem.
- To understand how a situation is likely to evolve over time and how potential decisions will affect the situation over time.
- To develop a good layout of the system's interface for efficient work of operators. This means displaying only relevant information, avoiding a messy or cluttered interface, and using a limited number of colours.

These identified needs formed the background for the development of an initial user interface concept. This concept is described in more detail in the next section.

2.4.5 Visualisation concept and interaction model

General approach to visualisation and interaction model

The interface primarily consists of a visual three-dimensional (3D) digital twin of the power grid. To enable external sharing of the results, the Nordic 44 grid was used as the basis for the design, see Figure 16. The proposed interaction model allows: (i) zooming in for more details and zooming out to see the whole picture; (ii) presenting the information in separate layers; and (iii) providing system recommendations for actions to be taken.

A limited number of colours have been used to avoid visual clutter. This is particularly important when observing several informational layers at the same time (for example, power oscillations and islanding).

The visualisation concept was created using the Unity visualisation platform. The main advantage of this platform is the ability to quickly create a 3D prototype and concept visualisations. The use of a 3D environment allows for utilizing the third dimension to visualise information, such as issues in the power grid.

Another major advantage of Unity is the possibility to present information in separate layers. This approach allows only relevant information to be displayed by activating a needed layer, thus avoiding a cluttered interface and information overload.

[34] ASAP (Advanced System protection schemes Applied in the Power grid): https://prosjektbanken.forskningsradet.no/en/project/FORISS/327728

Through the interface of the concept, the user can access various types of information by enabling different information layers and zooming in and out. For example, the user can activate a layer that displays the current production in different areas (see Figure 21, point (1)). By zooming into the 3D model, the user gains more detailed information, such as the production status at specific locations within the grid (see Figure 21, point (2)). It is also possible to activate subnetworks (sub-transmission or distribution grids) and see how they connect to the transmission grid. These subnetworks are positioned beneath the transmission grid in the 3D environment, allowing the user to view the connection points between the two grids (see Figure 21, point (3)). The concept also includes an interactive timeline that allows the user to view the network's status during relevant events.

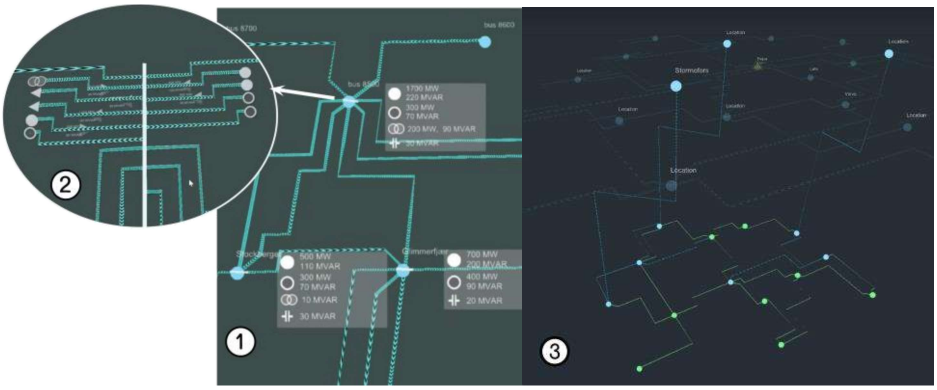

Figure 21: Overview of the user interface. A specific information layer shows production status in different areas (1). Zooming in on a part of the grid provides more detailed data, such as power production, consumption, active and reactive power and their directions (2). Zooming into a subnetwork (3).

By clicking on a certain production unit, a user gets more information about the power plant (see Figure 22).

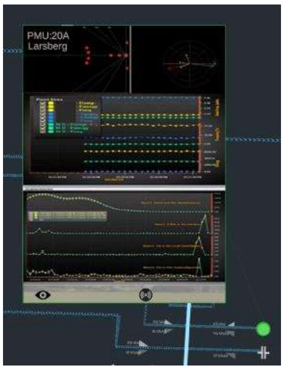

Figure 22: Info-box with the information about the power plant.

To illustrate the use of the interaction model, two different user scenarios were implemented into the concept. These scenarios demonstrate how the operator and the system work together to solve two different issues in the power grid, while allowing the human to maintain situational awareness. The scenarios are (A) Handling dangerous power oscillations, (B) Handling an islanding situation. The scenarios and their key visualisation components are described below.

Scenario A: Handling dangerous power oscillations

This scenario depicts a process of handling of power oscillations occurring in the grid. Using the interface, the operator monitors the power grid through a comprehensive overview image as shown in Figure 23. A potentially poorly damped oscillation is detected and flagged by the system with a yellow symbol, Figure 23, point (1), prompting the operator to engage the "Oscillation information layer" via the information layer selector menu Figure 23 point (2)[35].

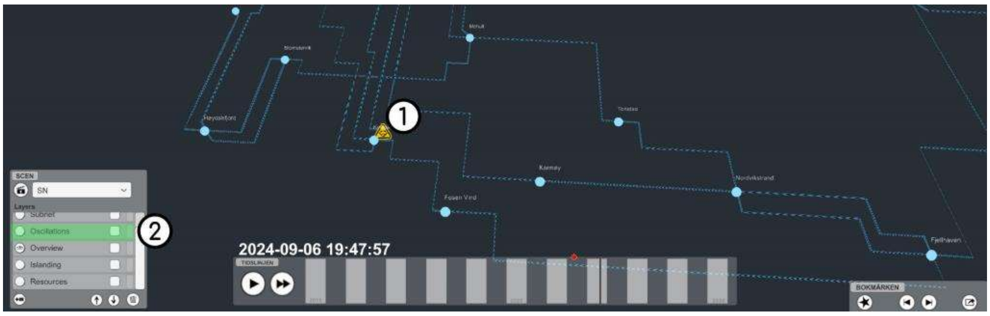

Figure 23: Overview of the user interface. Indication of oscillation is displayed through a symbol (1). The user activates the Oscillation information layer for more information (2).

In this scenario, the idea of a heat map was used to map the oscillations. However, in order to keep the visualisation as clean as possible, only relevant grid points were colour-coded to indicate oscillation levels in the grid: yellow for moderate oscillations, and red for critical oscillations, see Figure 24. Grid lines under high oscillation risk are also accentuated with a red outline and an oscillation symbol[35].

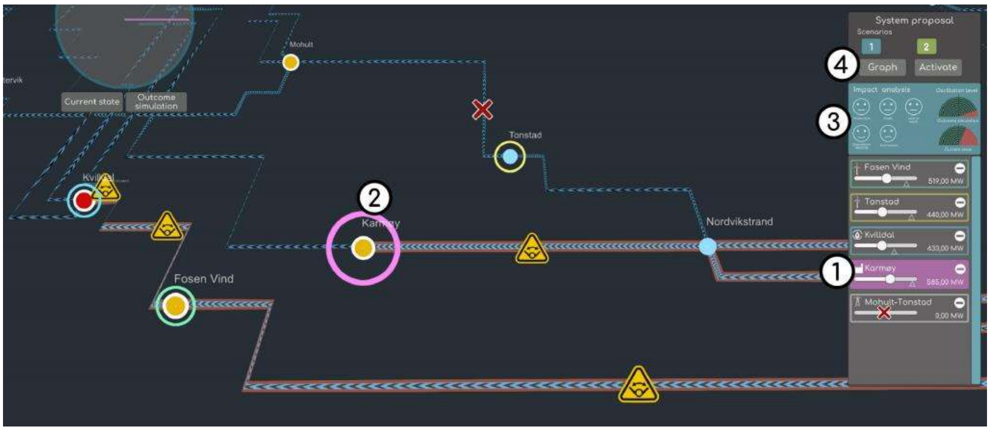

Figure 24: Oscillation information layer, including: list and location of suggested interventions in a menu (1), the position of each intervention, which is also visualised in the grid (2), the "Impact analysis table" (3), and a button to open system's prediction of oscillation behaviour (4).

To assist in resolving the oscillations, the operator consults a menu containing system-recommended interventions as shown in Figure 24. These recommendations are the outcome of an online dynamic security assessment tool, expected to be an integration between an automated model-based analysis tool of various control actions and an AI enhanced historian analysis function. This menu Figure 24, point (1) lists suggested actions (e.g., reduction of load) at specific locations, each highlighted in the grid overview with a coloured ring, Figure 24, point (2). The operator can also tailor the actions manually, including adding or removing interventions or altering their parameters (e.g., amount of load to reduce)[35]. An "Impact analysis" table in the menu Figure 24, point (3) provides further insights into the system's predictions / estimates of how interventions will affect the grid operations in terms of production, cost, loss of loads, operational reliability, and the environment. Expanding the table reveals a brief written summary of the system's interpretation of the

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[35] Hillberg, E., et al., *Standards-based interoperable testbed for development and assessment of stability monitoring applications in the Nordic interconnected grid*, CIGRE, Paris, 2024

oscillation event, including e.g., identified problem sources, helping to support the operator, to gain situational awareness and to evaluate the appropriateness of suggested interventions (Figure 25)[35].

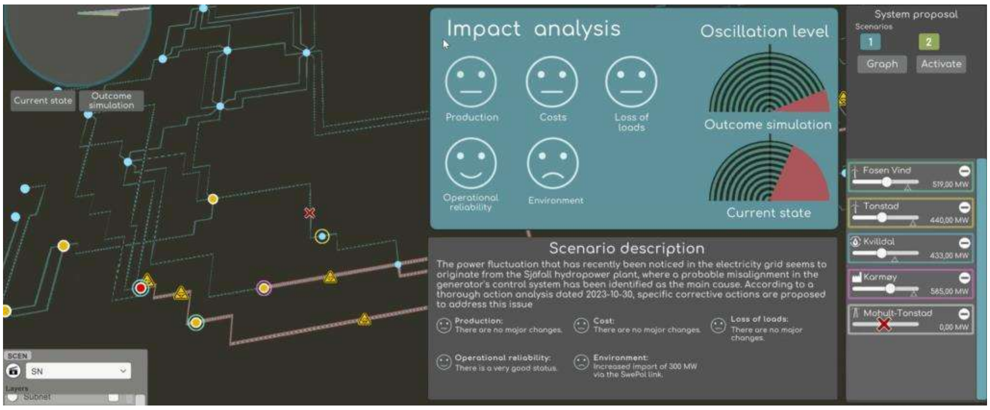

Figure 25: Oscillation information layer: expanded "Impact analysis table".

For an analysis of the oscillations, the operators can view a prediction of the oscillation behaviour Figure 24, point (4), indicating remaining time until the issue becomes critical. To facilitate understanding of the effect of interventions, the graph also displays predictions indicating their effect on oscillations over time. To enhance readability, it is also possible to see data as lines displaying the oscillation amplitudes over time, see Figure 26[35].

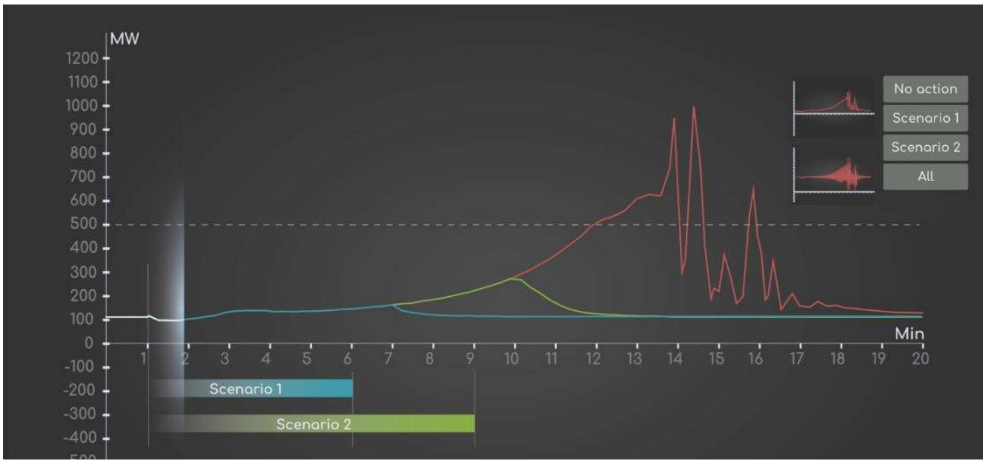

Figure 26: The system's prediction of the oscillation's amplitude in MW over time for two remedial action scenarios 1 (blue) and 2 (green), and the scenario without intervention (red).

If the operators modify, remove, or create their own interventions, the presented predictions in the interface change in real-time, which allows the operators to quickly gain insight into how the changes are expected to affect the situation.

Scenario B: Handling an islanding situation

This scenario depicts an islanding situation occurring in a part of the grid. When the islanding situation occurs, the system prompts the operator to activate the "Islanding information layer" via the information layer selection menu in Figure 27, point (1).

Using the capabilities of the 3D-visualisation environment, the island is dynamically visualised as an area in the grid that rises above or below the level of the rest of the grid, depending on the frequency of the islanding area, see Figure 27, point (2). Disconnected grid lines are indicated by a red colour and a red cross symbol. A black line means that the line is physically broken and needs to be repaired, see Figure 27, point (3).

The user interface follows the same approach and pattern as in the oscillation scenario. To assist the operator in resolving the islanding, the system provides recommended interventions in a menu in Figure 27, point (4). This menu lists suggested actions to be taken at specific grid points, which are highlighted with a coloured ring in Figure 27, point (5). The operator can also manually tailor the actions, including adding or removing interventions or changing their parameters (e.g., amount of load to be reduced).

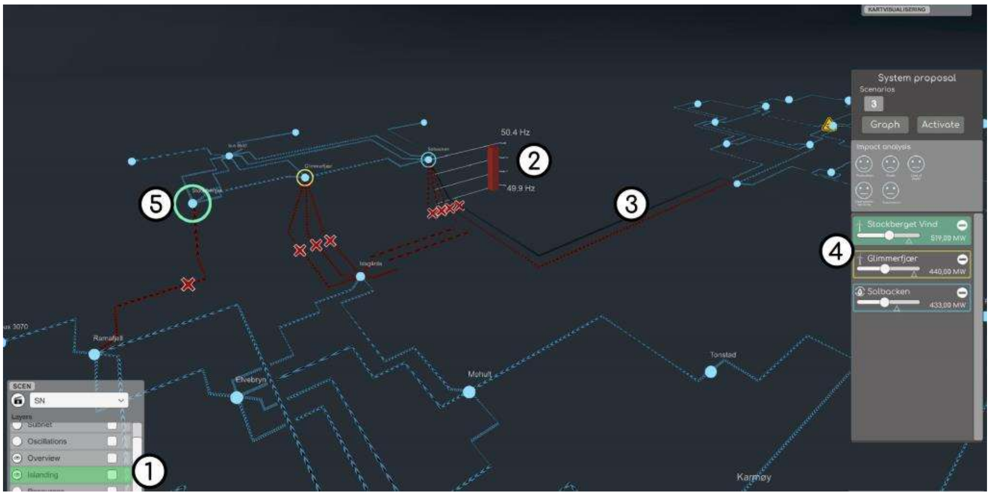

Figure 27: Visualisation of islanding scenario. The user activates the Islanding layer in the layer menu (1). The area of the islanding is elevated in the transmission grid (2). Physically broken line that needs to be repaired (3). Recommended interventions to solve the islanding (4). Selected interventions are also extra highlighted in the transmission grid (5).

An "Impact analysis" table in the menu (see Figure 28) provides a summary of how the system's proposed interventions will affect the grid operations in terms of production, cost, loss of loads, operational reliability, and environmental impact.

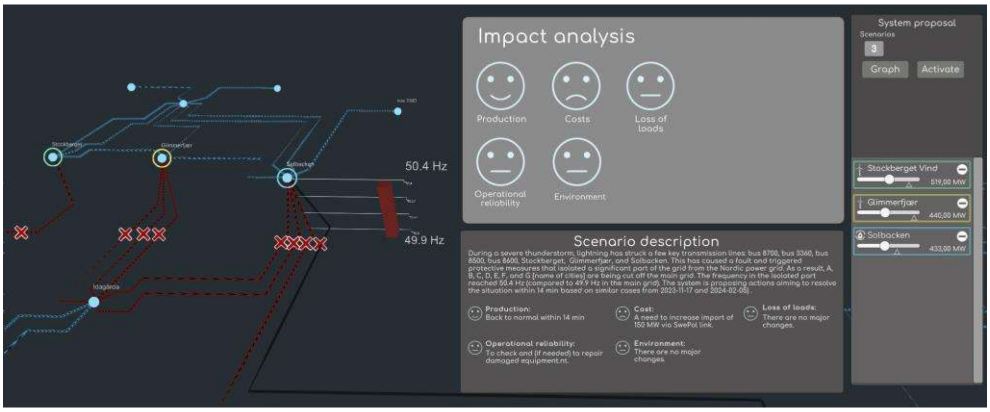

Figure 28: Islanding information layer: expanded "Impact analysis table".

For an analysis of the islanding, the operators can view a system's prediction of the situation development, indicating at which time and in which grid location a certain intervention should be taken, see Figure 29.

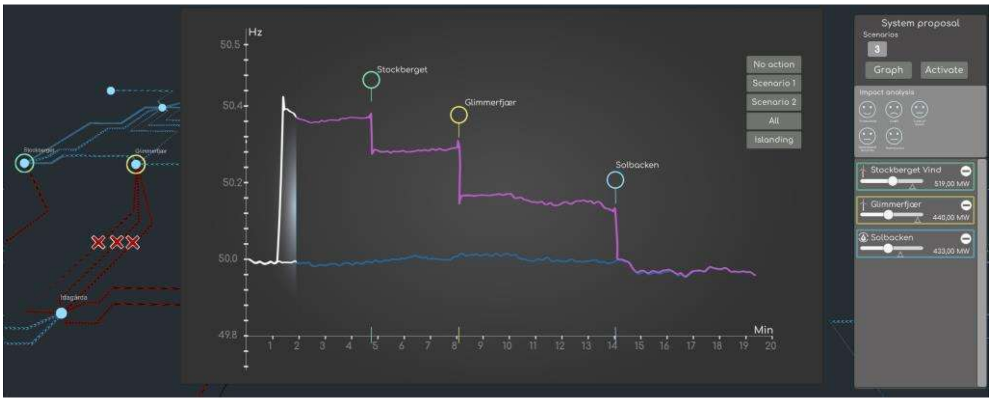

Figure 29: The system's forecast of the islanding development and proposed interventions at specific locations and time.

If needed, both scenario A and B (power oscillations and islanding) can be visualised simultaneously, see Figure 30.

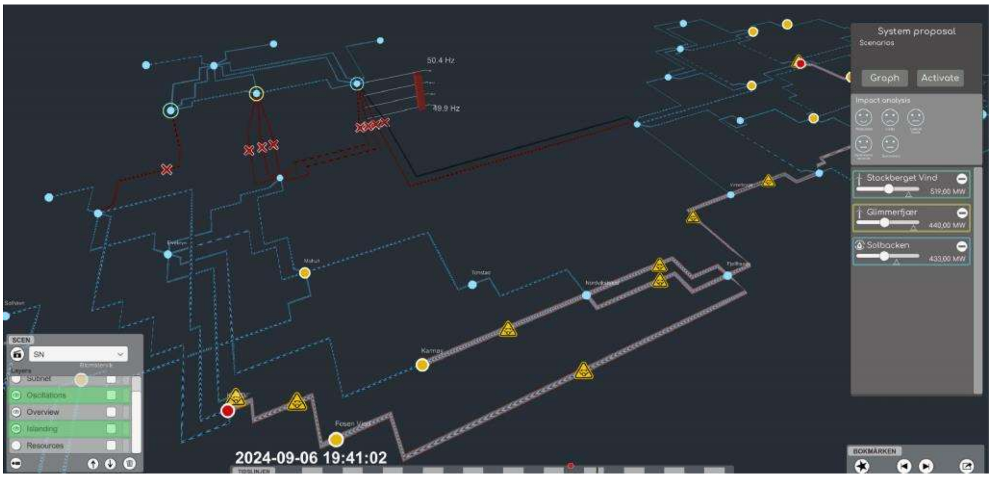

Figure 30: Combined view of both scenarios.

2.4.6 Value of the proposed visualisation concept

The major value of the proposed visualisation concept lies in envisioning future-oriented scenarios of how a human operator, on the one hand, and an advanced technology incorporating elements of AI and big data analytics, on the other, can work together to solve problems in real time. This approach implies a change in the working methods, where technology and humans play complementary roles.

As a result, interaction design is needed to support this interaction, as well as new ways of data visualisation that allow the operator to easily access information for decision making and influence. The interaction between the IT system and the operator leads to an improved ability to see the predictions of the situation development and possible consequences that the system can provide. All this leads to an improved situational awareness and decision making.

It is also important to mention that the visualisations are more focused on demonstrating the concept of this interaction rather than on proposing the exact implementation of such a functionality in the final version of a platform or tool.

Input from concept demonstration

No formal user evaluation of the interface concept has been performed. However, the concept was demonstrated at workshops for the Nordic TSOs and members of the project consortium and received positive feedback from the participants. In their daily work, TSO operators must monitor several different applications and significant amount of data. Therefore, they would appreciate a system that would assist them to maintain situational awareness, guide their focus to the required place in the grid, and provide efficient navigation with a reduced number of interactions to access information.

In general, TSOs found the concept's employed 3D view, information presented in separate layers, zooming in and out functionalities, and integration of data from different and multiple sources to be helpful. They also saw value in using the timeline to analyse historical data and to run future simulations when monitoring changes and deviations in real time.

2.4.7 Conclusions

A future-oriented visualisation concept for a WAMS / WAMPAC system was developed in the NEWEPS project. The novelty of the proposed concept lies in the ambition to design an interface that facilitates the collaboration between humans and advanced data analysis systems, where each part has a vital role to play. The solution serves as a starting point for future developments in interaction design and a guide for the advancement of underlying technology[36]. The development of the concept followed the principle of iterative service design.

The concept proposes visualisations for two scenarios: the handling of dangerous power oscillations and the handling an islanding situation. In the suggested design, the technical system quickly detects and analyses problems and proposes interventions. Concurrently, it offers operators information to maintain situational awareness about current and forecasted states, along with the system's working basis for tailoring own actions[36]. The proposed concept is designed to work with real-time data integrating PMU data and data from different technical monitoring systems. Assuming that in the future it will make massive flows of data, the proposed concept will enhance situational awareness of the operators and provide a support when managing critical situations in real time. At the same time, it will be helpful when analysing and learning from historical events, or as part of an operator training platform[36].

2.5 Summary

The architectural and data quality perspectives presented in this chapter highlight that development and implementation of WAMS and WAMPAC require a strategic and structured approach, as they play an important role in enhancing grid stability and security.

While several use cases for WAMS and WAMPAC have been identified, WAMPAC is inherently more critical and advanced in its applications, as it directly influences real-time grid operations. Thorough assessments and evaluations are therefore of highest importance to establish a foundation of trust and reliability. To gain trust and reliability is also a must for WAMS before its full potential can be realised. There is a need to clearly set the fundamental requirements and quality assurance. The integration between monitoring (WAMS) and control/protection (WAMPAC) needs to consider the differentiation in requirements of these two functionalities. In[37], this is highlighted stating that:

WAMS "*is used to understand the overall network dynamics and for increasing the situational awareness of the operators …. As a result, data completeness is more important than data latency.*"

WAMPAC *"systems need to react slow (some seconds) or fast (within few hundred milliseconds). For fast reaction data latency is more important than data completeness.*" WAMPAC "*systems are intended to run with highest availability and security, thus access to those systems by high number of users or applications should be strictly limited."*

"As a result, WAM and WAMPAC systems should be designed differently and implemented separately."

[36] Hillberg, E., et al., *Standards-based interoperable testbed for development and assessment of stability monitoring applications in the Nordic interconnected grid*, CIGRE, Paris, 2024

[37] CIGRE Technical Brochure 917, WG C2.18, *Wide Area Monitoring Protection and Control Systems - Decision Support for Operators*, CIGRE, 2023

However, for both WAMS and WAMPAC, having reliable data is absolutely crucial.

[37] presents three different architectural principles for WAMS and WAMPAC:

1. Separate PMU.
2. Separate data streams from same PMU.
3. Forwarding from WAMPAC to WAMS.

Furthermore, it is recommended that PMUs used for WAMPAC solutions are of performance **class P**, whereas PMUs with performance **class M** are deemed sufficient for WAMS applications. A continuous rollout of PMU installations across the grid is also important to ensure good coverage and sufficient data quality as some equipment needs to be replaced. There are different approaches and levels to integrate WAMS with the existing EMS monitoring system in the control centre. WAMS could be implemented as a separate system or be fully integrated in the EMS/SCADA with different pros and cons.

The European awareness system (EAS) currently facilitates real-time information exchange between European TSOs. The integration of PMU-data is ongoing and aims at enabling a broader perspective on grid conditions and reinforcing system resilience on a continental scale.

There is a need to harmonise the integration and implementation in the overall system architecture to meet the needs in terms of availability, security zones and reliability.

- Communication artefacts as latency, jitter and data loss in the data communication as well as malicious measurement substitution/spoofing, affects the application results in the measurement results. Notoriety is required in the implementation of communication networks to achieve sufficient measurement integrity. Various techniques for achieving high integrity in WAN communication are available, and the capabilities are constantly improving.
- A measurement based WAMS relies heavily on precise measurements. Permanent deviations in measurement results and transient artefacts (e.g. in communication solutions, measurement sources and time sources) can significantly affect the application assessments. It is therefore necessary to assess and handle such measurement uncertainties.
- The capabilities of the applications in a measurement based WAMS as well as the quality of their assessments will be greatly improved by state estimation and model awareness. For closed loop control with high integrity, a state estimation is necessary.
- For consistent situation analysis, the models in the various control systems must lead to comparable results in the various systems. This particularly applies to the criticality assessment of incidents, the root cause analysis and concluded actions.
- High system heterogeneity (one monolithic system VS many subsystems) gives greater flexibility, but also greater complexity. This requires maturity in the application solutions - and especially in the integration architecture.
- The same applies to virtualisation of computing environments such as micro services and containerisation. Virtualisation provides such great functional values for application development and testing that it is an inevitable trend, also in third party solutions, as exemplified in the NEWEPS Test & Demonstration platform presented in chapter 3.
- Effective development of WAMS applications relies on knowledge of experienced phenomena and available data. This requires off-line solutions such as big data timeseries databases and machine learning.
- Effective development and tuning of dynamic assessment applications is also greatly benefited by simulation of power system instability - with controlled complexity (such as noise).

As WAMS and WAMPAC are dependent on time synchronised measurements, the distribution of high accuracy common time reference throughout the PMU network is a critical requirement. [38] describes different time reference sources and standardised technologies to distribute time, relevant for PMU based applications.

This chapter also presents a future-oriented user interface design concept for improving interactions between human operators monitoring the power grid and WAMS/WAMPAC systems. Developed with Nordic TSO representatives and implemented in Unity, the concept features a zoomable 3D power grid visualisation with dynamic information layers to enhance situational awareness. The concept emphasises collaboration between human operators and the technical system. The proposed solution supports operators throughout the decision-making process by providing capabilities including: (1) continuous monitoring of critical events, (2) intervention recommendations, (3) event descriptions to enhance situational awareness and improve transparency regarding system-proposed interventions, and (4) forecasts of future grid states based on operator decisions. The human-system interaction is demonstrated through two use cases: managing dangerous power oscillations and addressing an islanding situation. This work lays a foundation for future research into user interfaces and supporting technologies for WAMS/WAMPAC systems. Several design features have inspired the solutions developed and implemented in the NEWEPS Test & Demonstration platform.

Overall, this chapter sets the foundation for the subsequent chapters, which delve deeper into the technical implementation and testing of the developed solutions.

[38] CIGRE Technical Brochure 884, JWG B5/D2.67, Time in Communication Networks, Protection and Control Applications – Time Sources and Distribution Methods, CIGRE, 2022

3 NEWEPS Test & Demonstration platform

3.1 Introduction

While it is likely that WAMS and WAMPAC systems will be deployed in the future Nordic power systems, it is challenging for the TSOs to provide detailed specifications of their requirements for research and development purpose. This leads to difficulties in the development and demonstration phases which can delay the adoption of these technologies.

In the NEWEPS project, a prototyping platform has been developed, referred to as the NEWEPS Test & Demonstration platform. This platform has the aim to illustrate, through prototyping, the features which a future WAMS & WAMPAC system could provide. Furthermore, the NEWEPS Test & Demonstration platform facilitate the necessary common environment where developed WAMS & WAMPAC applications and solutions within the NEWPES project have been tested, validated, and demonstrated efficiently. This also includes the integration and investigation of coordination and visualisation concepts.

The NEWEPS Test & Demonstration platform was developed iteratively through repeated cycles of collection of needs and developed ideas, implementation of functionalities, demonstrations to users, collection of feedback, and refinement. An effort was made to keep the platform lightweight and easily deployable.

This chapter first provides a description of the NEWEPS Test & Demonstration platform including an overview of its architecture, component functional blocks and main features including a list of applications integrated in the platform. Moreover, this chapter provides an overview of the activities carried out to integrate the platform with laboratory facilities in order to allow the testing of WAMS & WAMPAC applications with real hardware (e.g. IEDs, merging units).

3.2 Platform overview

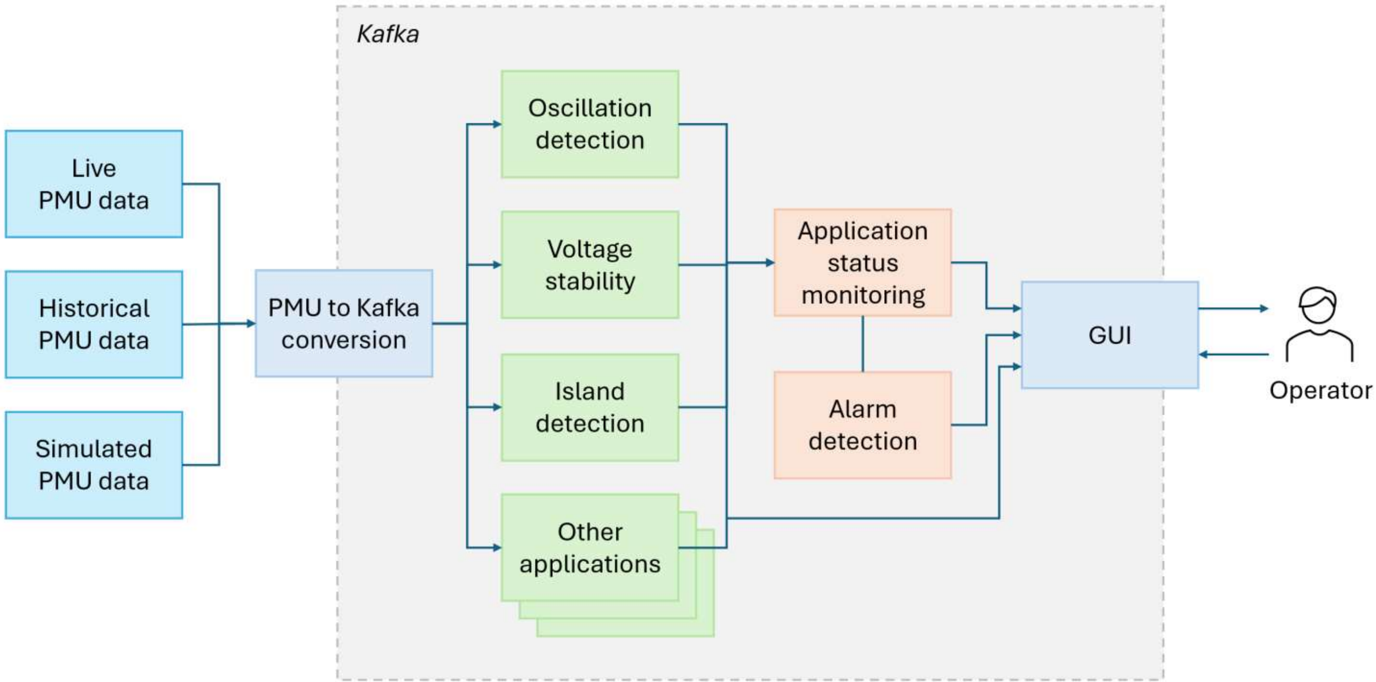

Figure 31: Overview of the NEWEPS Test & Demonstration platform architecture

It was agreed early in the project that an application-based architecture was desirable consistently with present trends of deploying microservice based architectures and with preferences for easily scalable and modular architectures. This architecture assumes multiple independent applications responsible for performing specific tasks and eventually interacting by exchanging data. The inputs and outputs of the applications need to be communicated via a network connection. In the platform this was based on Kafka. Figure 31 presents an overview of the NEWEPS Test & Demonstration platform, and its interface to the operator in form of a graphical user interface (GUI) and to the power system in form of standard based PMU data streams originating from simulations, historians, or on-line measurements. In addition, the NEWEPS Test & Demonstration platform has an integrated dynamic simulator built in Python, TOPS (Tiny Open Power System Simulator), where the Nordic 44 model is implemented and used for online test and demonstration purposes.

The application-based architecture is beneficial for scalability of the system (e.g., new functionality can be introduced by starting a service on a new computer connected to the same network), and stability/security (if a service fails, it does not necessarily affect other applications, and it can be restarted without having to restart the whole system). An example of an application in the WAMS setting could be a service for processing raw PMU data from the PDC, detecting bad data, improving/"cleaning" the data for other applications (e.g., substituting missing values, etc.). Another application could process measurements and provide stability indicators (e.g., voltage stability). Yet another application could monitor the status of other applications and give a notification in case an application crashes and possibly restart the application. visualisation applications would use data or output from other applications but only provide visual output.

Code collaboration was enabled by using Git for version control, and the repository with the code has been stored on GitLab[39]. Code development in different work packages was generally done in separate, independent repositories, before finalised versions of new functionalities were transferred and introduced into the common repository.

The platform is also described in[40], and in the documentation, which is accessible through the GitLab repository.

3.3 Platform implemented functionalities

The platform offers general purpose functionalities to facilitate the implementation, testing and demonstration of additional applications. Moreover, a few example applications are integrated and can serve as templates.

The most relevant platform functionalities can be summarised as:

- A streaming platform based on Kafka to handle communications between the applications.
- General purpose functionalities that can be re-used and that address common application needs (e.g. reading PMU data frames, reading model data, mapping measurements to components, etc).
- Templates for real-time applications that can serve as a basis when introducing new applications.
- Testing functionalities enabling multiple modes of testing new applications (e.g. development scripts, simple unit-tests, real-time simulation tests).

[39] https://gitlab.sintef.no/neweps/neweps

[40] H. Haugdal, S. d'Arco, K. Uhlen, A Platform for Development and Testing of WAMPAC Applications based on Kafka Streaming, IEEE PES Innovative Smart Grid Technologies Conference, ISGT, 2024

3.3.1 Monitoring applications

Specific applications aimed at detection of instabilities or abnormal operating conditions implemented in the platform include the following:

- **Oscillation monitoring**: Three applications targeting oscillation monitoring, two of which are based on system identification techniques SSI (Stochastic Subspace Identification) and N4SID (Numerical algorithms for state space system identification), and one based on FFT (Fast Fourier Transform). The N4SID and FFT applications were implemented as placeholders, before the SSI application, which is based on developments described in chapter 4.3, was implemented.
- **Voltage stability**: A voltage stability monitoring application is implemented, based on the developments described in chapter 4.2, which is able to provide three different voltage stability indicators (VSI) - AA (Adaptive Approach), AD (Adaptive Method), SZI (S-Z sensitivity Indicator).
- **Island detection**: An islanding detection application is implemented based on a frequency-difference identification method.

In addition, an application for Security Constrained Optimal Power Flow (SCOPF) is implemented based on the results from the ASAP project[41]. The various implemented visualisation applications are described further in section 3.5.

3.3.2 Kafka streams

The Kafka stream processing framework has been selected for integrating applications in the platform and for establishing communication between individual applications. Kafka is widely trusted and considered stable and fault-tolerant, for enabling the streaming/communication of data between applications in an efficient and scalable manner. Moreover, Statnett recommended this choice based on positive experience from previous projects.

Kafka requires setting up a server, and *producers* and *consumers* can connect to the server. Data on the server is organised in *topics*. Producers send data to topics while consumers obtain data from topics in the same order as it was sent to the server.

Kafka topics in the NEWEPS Test & Demonstration platform include:

- A PMU data topic, which holds C37.118 standardised data frames from the PDC (where data from all PMUs is in the same data frame),
- An application status topic, containing status messages sent from running applications,
- A topic for alarms and messages related to alarms,
- WAMS & WAMPAC assessment topics, including separate topics for voltage stability indicators, detection of oscillatory modes (eigenvalues and observability mode shapes), and islanding detection results.

As setting up a Kafka server requires some effort, a simple Kafka alternative was implemented in addition, “Not-Quite Kafka” (NQKafka), which can be thought of as a “mock-up” in programming terminology. This alternative depends only on Python, and allows running simple, short-lived setups without connecting to a proper Kafka server. Thus, the user can decide on one of these two alternatives based on the specific needs.

[41] ASAP (Advanced System protection schemes Applied in the Power grid): https://prosjektbanken.forskningsradet.no/en/project/FORISS/327728

3.3.3 Interfacing simulation-based PMU files

In order to enable simulation-based validation of WAMS & WAMPAC applications, the NEWEPS Test & Demonstration platform is equipped with an interface to read files created to emulate real PMU streams. The input file format is based on csv, where each input file (representing an emulated PMU), contains values related to one bus in the simulation model including information about: bus frequency, bus voltage, currents through branch elements (lines and transformers) connected to the bus, as well as currents to loads and generators connected to the bus. The input file data are structured as indicated in the table below, with the time step between each time stamp equals 0.02 s. During the simulation-based application validations in the NEWEPS project, the simulation software PSS/E was used together with a Python based simulation framework to automatically create the PMU files.

Table 3: Structure of the simulated PMU data files.

File name	date_ PMU_B12345.csv		
Type of channel	**Channel name**	**Unit**	**Comment**
Time	Timestamp	s	
Frequency	PMU_B12345: Frequency	Hz	
Bus voltage	PMU_B12345: V3_Magnitude	V	
	PMU_B12345: V3_Angle	Rad {-π to π}	NaN is replaced with 0
Branches	PMU_B12345:B*56789* _*ID*_I3_Magnitude	A	Main current (not the phase current, assuming a balanced situation)
	PMU_B12345:B*56789* _*ID*_I3_Angle	Rad {-π to π}	NaN is replaced with 0
Generators	PMU_B12345: *ID*_G_I3_Magnitude	A	Main current (not the phase current, assuming a balanced situation)
	PMU_B12345: *ID*_ G_I3_Angle	Rad {-π to π}	NaN is replaced with 0
Loads	PMU_B12345: *ID*_LD_I3_Magnitude	A	Main current (not the phase current, assuming a balanced situation)
	PMU_B12345: *ID*_ LD_I3_Angle	Rad {-π to π}	NaN is replaced with 0

In the table the following conventions are adopted:

- *date: date the file is created in format yyyy-Mon-dd_hh-mi-sec,*
  e.g. 2024-Jun-11_14-10-51
- *12345: bus number to which the PMU is connected*
- *56789: bus number in the other end of branches connected to the PMU bus*
- *ID: Element id, to distinguish between parallel elements connected to the bus*

3.4 Coordination and alarm handling logic

Functionalities for issuing alarms and visualizing information related to alarms were implemented in the platform together with a scheme for enabling coordinated communication between neighbouring TSOs. Two main types of coordination have been addressed:

1. Coordination of several WAMS or WAMPAC applications for a single TSO, referred to as **Local TSO coordination**
2. Coordination between more TSOs especially concerning sharing information on the state of the grid and possible reasons of concerns or faults, referred to as **Inter TSO coordination**

3.4.1 Alarms handling

Modules producing alarms can be viewed as a form of coordination of information. The alarm can inform that a critical instability, disturbance or event was detected, which requires the attention of an operator, and should be presented in a clear and informative way. Alarms could also be accompanied with further information regarding where and when the event was detected, how it was detected, and where to look for further details (e.g., showing Visualisations and/or plots of relevant measurements). This is an effective way of guiding the attention of the operator towards relevant or critical information. In the NEWEPS Test & Demonstration platform, introducing alarms was supported through feedback from the participating TSOs, requesting the ability to communicate with other operators and other TSOs regarding ongoing events/instabilities since such features are not yet available. The type of communication includes acknowledging events/instabilities and a messaging system to replace phone calls.

An alarm raised by an application at a defined time for a specified reason (e.g., threshold logic) can serve as a pointer towards an issue that has been identified and that possibly should be addressed. The ability to manually silence and hide previous alarms should be available for the operators. However, if we impose the rule that alarms cannot be deleted/removed but will be recorded, we can make sure that acknowledgements, messages, etc. from operators can be preserved and eventually utilised afterwards.

Equally important to showing alarms when something critical happens, is to not show alarms when nothing critical happens. Similarly, modules should not provide more alarms than necessary. For example, a case of continuous oscillations lasting for some minutes should ideally produce only one alarm.

The simplest threshold logic for when to provide an alarm would be to raise an alarm when the threshold for the stability indicator is exceeded. A limitation of this scheme is that many alarms would be raised in a short time for the same instability if the stability indicator is close to the limit passing the threshold multiple times. For example, this would occur for a module estimating the damping of oscillations between 4% and 6% with a threshold of 5%.

One solution to this is to introduce a minimum time that the indicator should be below the threshold before a new alarm is issued. The advantage of this scheme is that it is very simple and easy to understand and implement but still allows provision of alarms at a reasonable rate. It should be noted that in the case of instabilities lasting for longer periods (significantly longer than the mentioned "minimum time"), a high number of alarms could still be produced for the same instability.

Prioritizing between different simultaneously raised alarms is a more complex form of coordination. This could be realised if different modules provided a measure of criticality along with each alarm. However, calibrating the criticality level between different modules targeting different instabilities is a challenge since the criticality level could depend on the particular operating conditions.

3.4.2 Local TSO coordination

Local TSO coordination relates to coordination of the information which should be relayed to the operators' interface. Stability monitoring modules produce information in the form of alarms, margins, assessment status (e.g. normal/alert/emergency), recommended decisions, etc. It is important that information from individual modules is shown in a cohesive and coherent framework filtering conflicting information and inconsistencies. Moreover, the operators should not be overwhelmed by a flow of irrelevant data and that the output of the monitoring modules is presented only when something relevant or important is detected and suppressed otherwise. The coordination effort includes both provision of thresholds used for a WAMS/WAMPAC module to raise an alarm, as well as provision of priorities if several modules raise alarms simultaneously. Furthermore, in case modules are proposing mitigative actions, the coordination of such actions will be necessary in order to prevent any counterproductive actions to be proposed by different modules.

3.4.3 Inter TSO coordination

Inter TSO coordination relates to the exchange of information between different organisations/TSOs. As the implementation of a WAMS/WAMPAC platform may be distributed between several TSOs within a synchronous area, there is an implicit need to coordinate the exchange of information between TSOs. Both the location and the severity of an alarm could be of importance in the sharing of information.

The most fundamental functionality should be an automatic system to let neighbouring TSOs know if there is a problem in the system. In the Nordic countries, such information sharing between TSOs is currently done by phone calls. This is inefficient, might be inaccurate, and causes unnecessary delays. Information which seems reasonable to share automatically includes the type of problem (oscillations, voltage problems, etc.), approximate locations involved, extent of the problem, whether the problem has been seen by a human ("acknowledged"), and whether mitigating actions have been planned. It should be noted that some information will not be possible to share due to their sensitivity (legal restrictions/confidentiality/internal regulations).

In the future, such system could be more advanced, supporting coordinated decision making between the TSOs. The system could propose mitigating actions automatically to other TSOs or allow operators to propose actions manually. Involved TSOs could then manually accept or decline the proposed action, or using automatic decisions from the system to accept or decline proposed actions from neighbouring TSOs automatically.

Building on the ideas in the previous section on Alarms, one simple inter-TSO information sharing scheme can be realised simply by sharing alarms with neighbouring TSOs. A filter could be applied to select which alarms to share, based on the characteristics of the problem, like locations involved, extent of the problem, etc. For instance, an alarm about local oscillations, which would be considered to have a negligible impact on the neighbouring power system, would not be shared. An alarm about voltage stability problems on an interfacing corridor, on the other hand, should be shared since the effect likely would propagate and impact both power systems. Furthermore, allowing users from both TSOs to acknowledge and send messages back and forth relating to shared alarms would eliminate the need for phone calls.

3.4.4 Platform implementation of coordination and alarm handling

To be able to demonstrate coordination module functionalities, implementations in the NEWEPS Test & Demonstration platform have been done for both type of coordination. The Local TSO coordination is based on thresholds, which can be changed by the user for each of the integrated WAMS/WAMPAC module. Alarm threshold levels can be fixed, based on experience, best practices, or regulation, or they could be variable depending on situation or location. The ability to manually adjust thresholds during operation has also been requested in project meetings.

For raising alarms, the scheme introduced in previous sections was implemented, reproduced here for clarity:

- An alarm is raised when an indicator exceeds the threshold.
- A new alarm will not be raised by the same module before the indicator has been below the threshold for a specified amount of time.
- When the application is allowed to issue a new alarm (according to the previous point), the previous alarm will be marked as “not critical”, indicating that the cause of the alarm is no longer urgent, and other alarms (if present) should be prioritised.

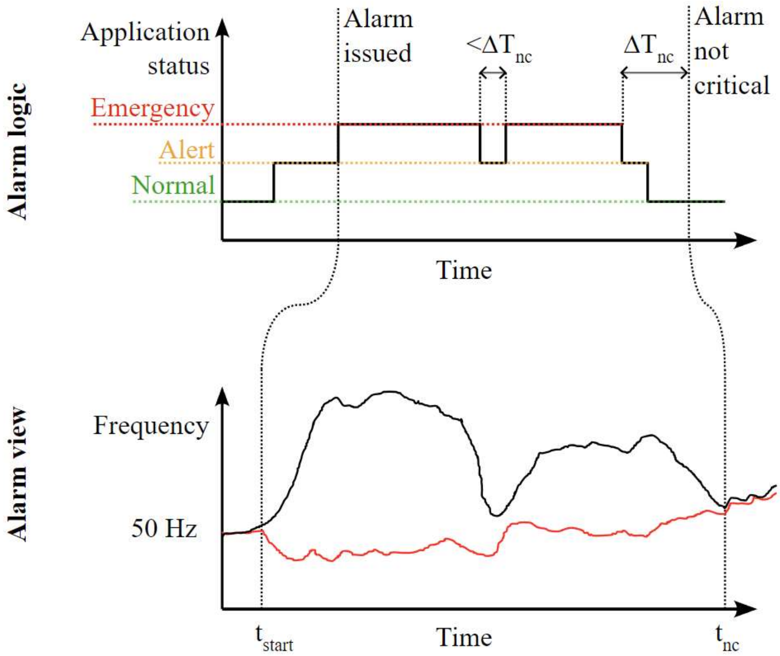

Figure 32: [Alarm logic]: Illustration of the logic determining when to issue alarms.

The time interval between the alarm is issued and it is marked as “not critical” can further be used to show relevant information about the alarm, which is referred to as “alarm view” in Section 3.5.3.

Once an alarm is raised by a monitoring module, the alarm is assigned a specific, unique ID. This alarm is then shown to all users of the NEWEPS Test & Demonstration platform. A GUI allows users to “Acknowledge”, “Annotate” (=send a message) and “Silence” the alarm, where each action is then tied to the unique ID of the alarm. In the GUI, all the events associated with the alarm are also shown chronologically.

Figure 33 Alarm overview. Indicating the time and the module which raised the alarm, and the status of the alarm

In the Inter TSO coordination implementation, the TSOs are expected to have access to different information. The most relevant data sources provide information on each TSOs specific grid, with additional information provided regarding events and actions from the other TSOs, as illustrated in Figure 35. When the coordination module receives information of a violated alarm level, alarm & visualisation becomes active for the local TSO while the other TSO becomes informed with possibility of looking into further details. Depending on localisation and severity of alarm, mitigative actions can be requested by both TSOs, and actions which are taken by one TSO are communicated to the other TSO.

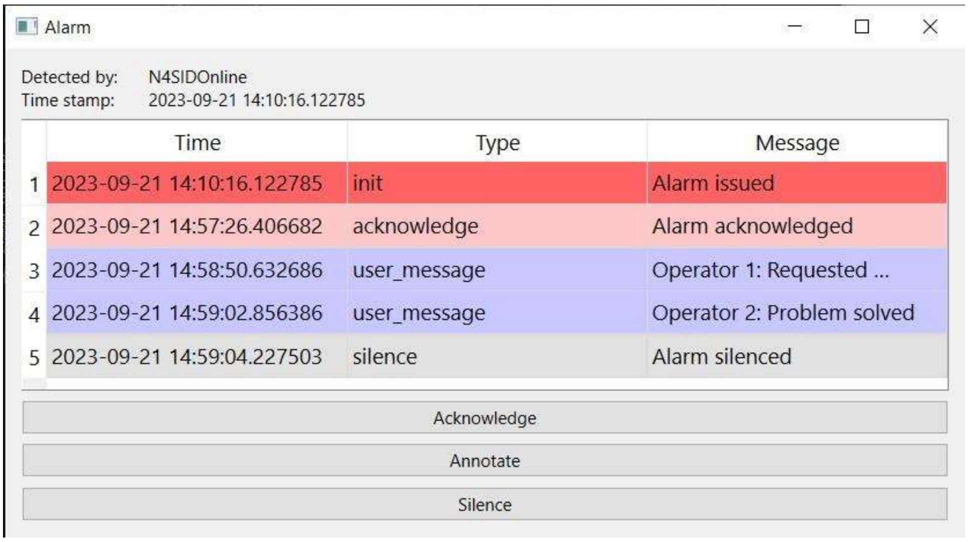

Figure 34 Handling alarms (accessed by double-clicking one of the alarms in the overview shown in Figure 33).

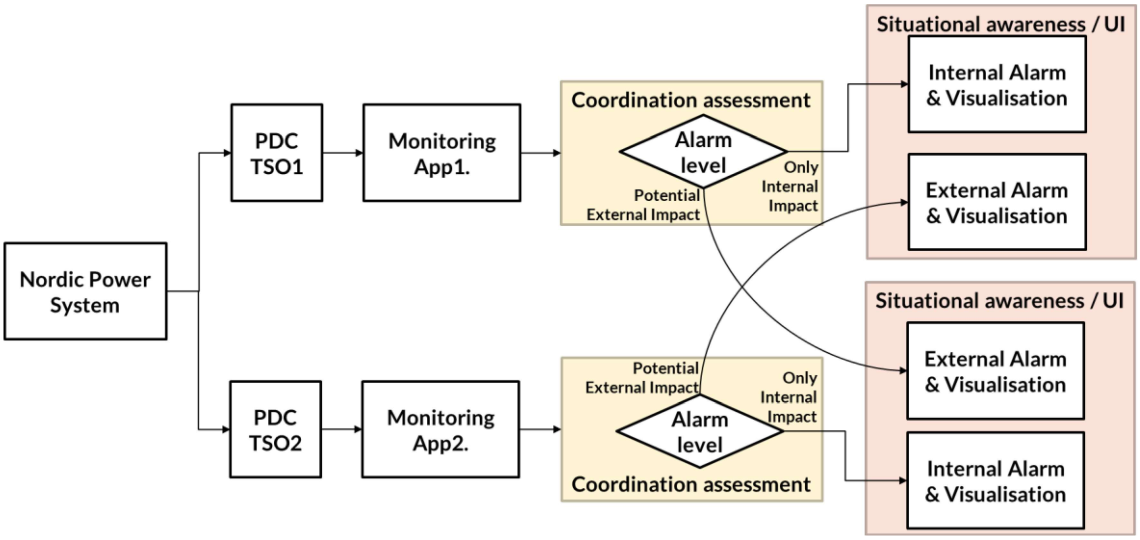

Figure 35 Illustration of Inter TSO coordination

In the NEWEPS Test & Demonstration platform, Inter-TSO Coordination is implemented in the form that alarms of each TSO are forwarded to other TSOs, along with information on acknowledging, silencing or related messages. The other TSOs can also perform acknowledging, silencing and messaging. An example of how this scheme works is indicated in Figure 36. Referring to the numbering (1-4) in the figure, the sequence of events is as follows:

1. A disturbance is detected in Sweden by Svenska kraftnät. In this case the stability indicator is amplitude of oscillations, estimated using an FFT-based monitoring application.
2. As the threshold is exceeded, an alarm is raised in Sweden.
3. The alarm is forwarded to Statnett (Norway) automatically.
4. The alarm is acknowledged by Svenska kraftnät. The acknowledgement is immediately also visible in Statnett's system.

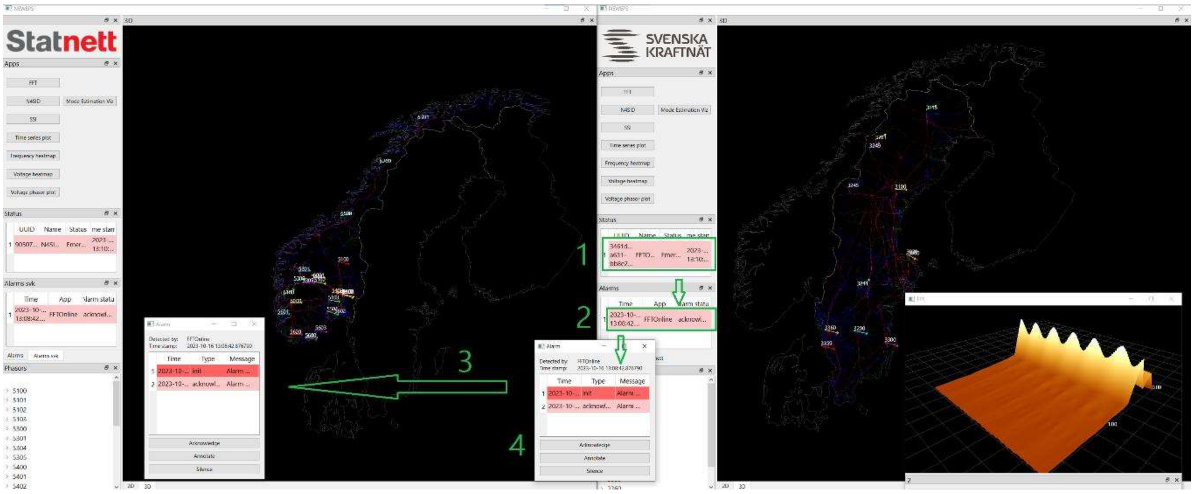

Figure 36 Example of Inter TSO Coordination. 1: Instability detected by Svenska raftnät, 2: Alarm raised, 3: Alarm forwarded to Statnett, 4: Alarm acknowledged by Svenska kraftnätk.

3.4.5 Further ideas

In the NEWEPS Test & Demonstration platform, it could be beneficial to have multiple monitoring modules/applications assessing the same kind of stability. E.g., multiple oscillation monitoring applications, some targeting standing oscillations and others targeting “ambient conditions”, where the system is excited/perturbed continuously by random load variations. One issue with this is that several modules could raise alarms for the same instability. For instance, if both a FFT-based oscillation monitoring application and a system identification-based application detected oscillations with high amplitude and low damping, both would raise alarms.

Ideally, only one alarm should be raised. One way of avoiding superfluous alarms could be to allow alarms to be merged/grouped, either manually or automatically. Automatic grouping of alarms could be achieved if each alarm was accompanied by a set of parameters characterising the alarm, for instance oscillation frequency and locations involved. Thus, if both a FFT-based application and a system identification-based application detected 0.5 Hz oscillations in a set of stations in northern Norway, it would be relatively easy to figure out that the two resulting alarms actually pointed to the same problem. Similarly for a voltage stability monitoring, alarms from two parallel applications could be grouped if they pointed towards voltage stability problems in the same location.

3.5 Visualisation concepts

3.5.1 Application-specific visualisations

Several visualisation applications aimed at showing results from specific monitoring applications have been implemented. These visualisations can be opened manually by the user and show the most recent assessment result.

Targeting oscillation monitoring, a mode estimation visualisation is shown in Figure 37. This visualisation shows estimated eigenvalues in the complex plane to the left, and observability mode shapes of a selected eigenvalue to the lower right. The identified modes estimated frequency can be read from the y-axis in the left figure and relative damping can be evaluated using the damping lines drawn for a set of pre-defined levels. The right figure includes values for the selected mode for each PMU signal evaluated. The small GUI to the upper right allows the user to navigate through available mode estimates. The GUI also allows for navigation between methods. The figure presents oscillation monitoring results identified with the N4SID method. Corresponding figures of eigenvalues and observability mode shapes can be presented for results identified with the SSI method.

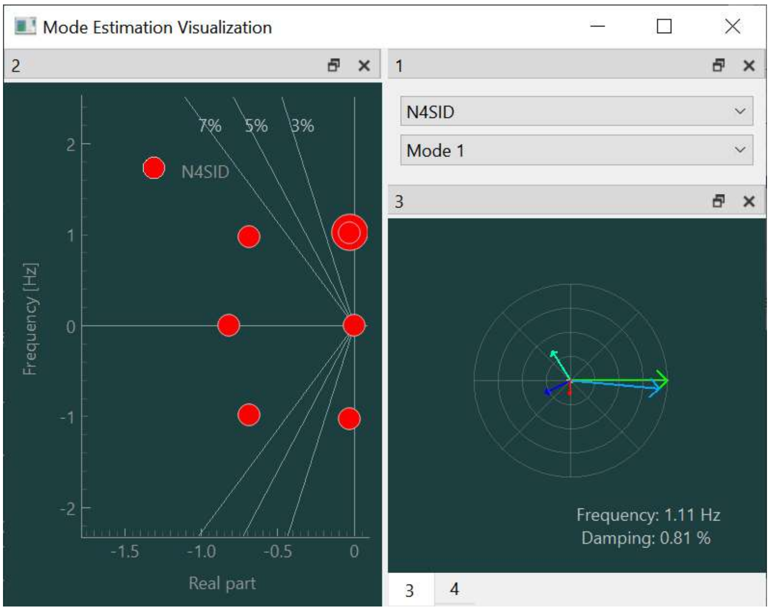

Figure 37: [Visualisation: ModeEstimation]: Mode estimation visualisation showing estimated eigenvalues and observability mode shapes.

The Fast Fourier Transform based visualisation in Figure 38 shows a surface plot that indicates amplitude of oscillations as a function of time and frequency. The GUI allows the user to select between individual channels (to the left) and adjust scaling factors (to the right) and thresholds for amplitude for determining assessment status ("Normal", "Alert" or "Emergency").

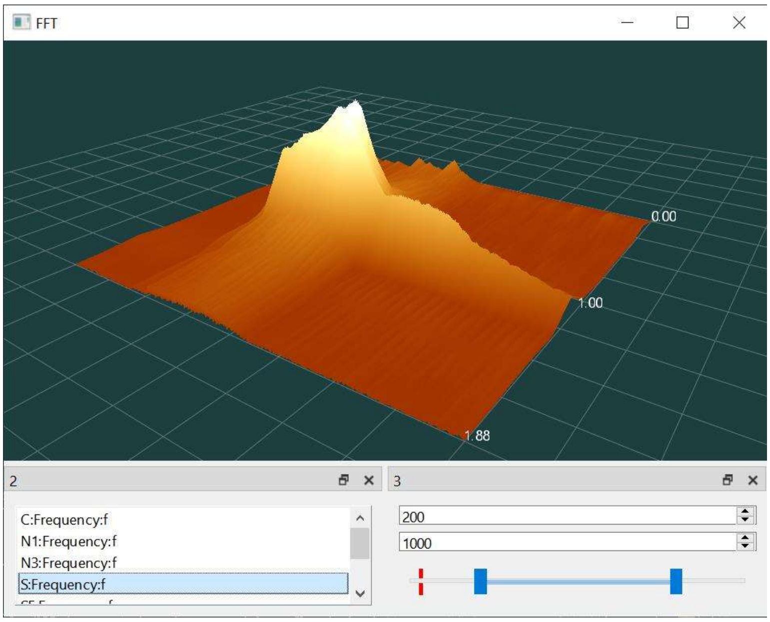

Figure 38: Fast Fourier Transform based visualisation, for showing amplitude of oscillations as a function of time and frequency.

Figure 39 shows an application for plotting time series. The stations with PMUs are indicated on the map, and channels can be selected by clicking a station and selecting a channel.

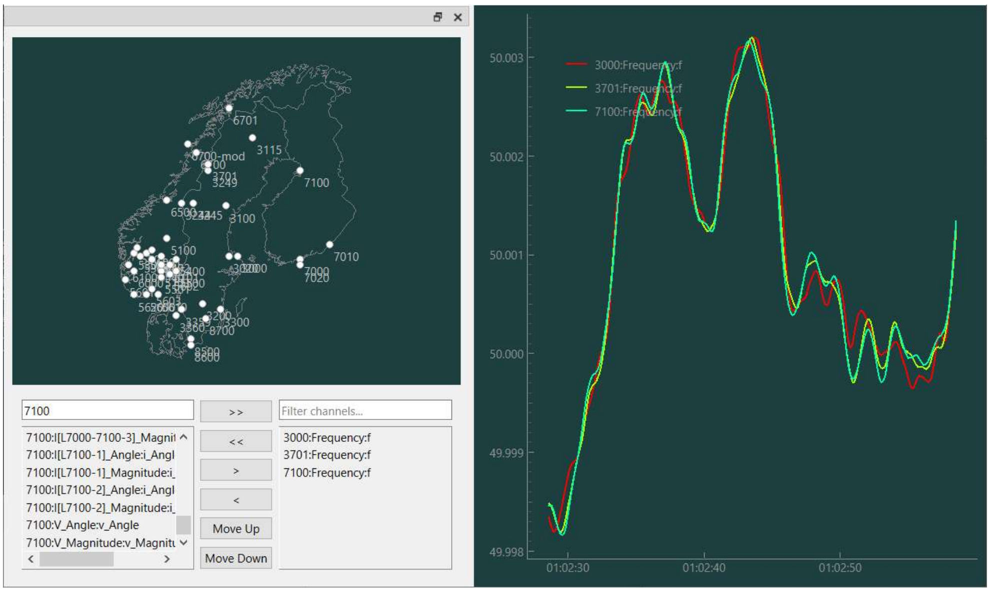

Figure 39: [TimeWindow GUI]: Time series plot with geographic channel search.

When it comes to voltage stability, the Voltage Stability Application opens in the status window of the GUI and raises an alarm when the voltage is critical (see Figure 44). The voltage stability application can be run using one of two sets of voltage stability indicators, the SZI or the AD. The Voltage Stability Monitoring window in Figure 40, that can be opened separately while the voltage stability application is running, shows the time series plot of the voltage stability indicators.

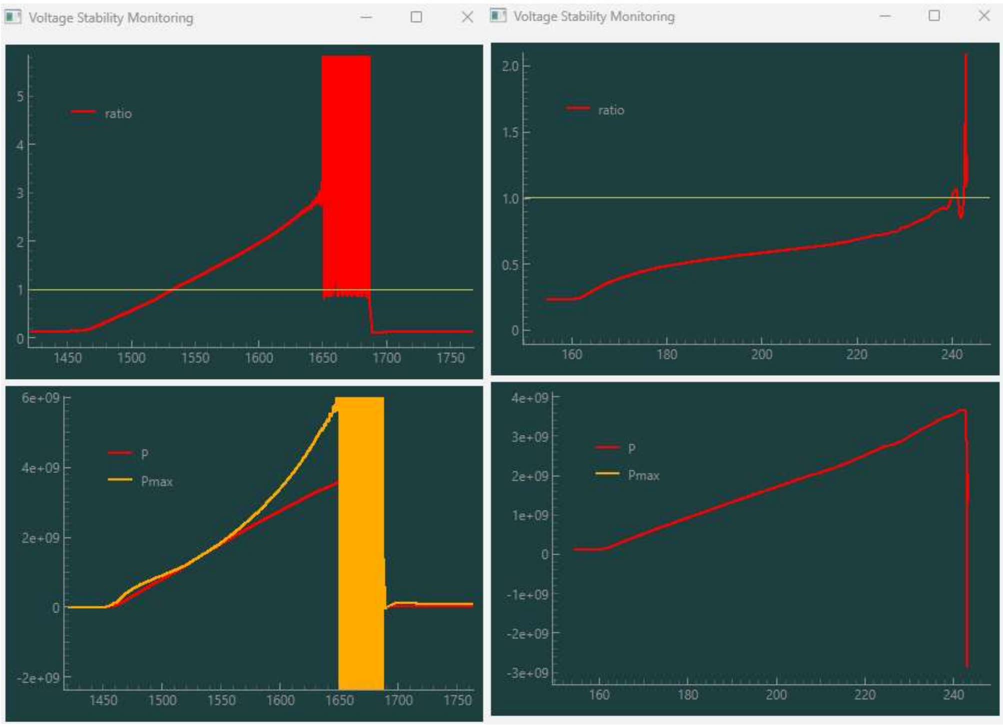

Figure 40: Monitoring of the voltage stability indicators (SZI to the left and AD to the right).

3.5.2 Single-line diagram layers

Indicating information by emphasizing, colouring, or modulating graphical elements in a single-line diagram is an effective way of conveying information on the location of events, problems or disturbances. In the NEWEPS Test & Demonstration platform, this is implemented based on the "layer" functionality described in section 2.4.

Some layers are presented in Figure 41, where the activated layers are indicated to the right, and the single-line diagram with active layers is shown to the left. Some of the available layers include:

- **Static line data:** A static single-line diagram (yellow lines).
- **Countries:** Geographic borders between countries.
- **Voltage phasors:** Phasors (shown in red in the figure) indicating the voltage amplitude and phase at buses around the system
- **Bus frequency:** The round markers at each station. The "altitude"/z-component of the marker position is proportional to frequency at the bus. This is a simple and effective way of indicating frequency variations around the system, in particular in the case of oscillations or islanding conditions.
- **Line outages:** Disconnected lines are indicated with red colours. In the figure, the line between 6500 and 5100 is disconnected.

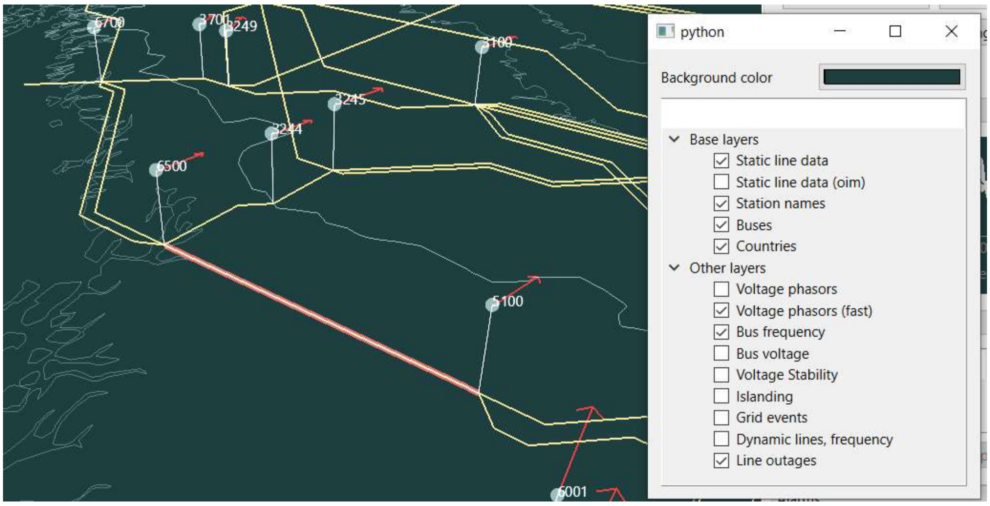

Figure 41: [Visualisation SLD Layers]: Visualisation layers in the single-line diagram

The layers can be activated or deactivated. Some layers require more information than others. For instance, indicating disconnected lines requires a single-line diagram in the right format to be available. In case this is not available, some of the layers will not be possible to activate.

Visualisation layers can also be activated automatically or be used to complement other functionalities. For instance, special visualisation layers are used for the WAMPAC solution (see chapter 5) to visualise critical contingencies and proposed remedial actions on the single-line diagram. Layers can also be used in "alarm views", as described in the following section.

3.5.3 Alarm views

In section 3.4.1, the logic for issuing alarms implemented in the NEWEPS Test & Demonstration platform is described. From this logic, certain metadata associated with alarms will automatically be defined, among others: the monitoring application causing the alarm, the time at which the alarm was given, and the time at which the alarm was marked as "not critical". This is information that can be used for creating specific visualisations that are tailored towards efficiently conveying information about an alarm. Such visualisations are referred to as "alarm views".

In Figure 42, an alarm view for showing alarms from the islanding detection applications is shown. The alarm view is opened by clicking the alarm in the alarm list (third box from the top to the right). The time of the alarm (start =alarm issued, and end =alarm not critical) is used to collect and show time series and monitoring results from the relevant period. If the "not critical" time is not yet defined (i.e., the problem is still ongoing), the time series plot will continue.

To the lower left in the figure, a timeline for the alarm is shown, indicating when (/if) it was issued, acknowledged, annotated, silenced, or not critical, and the monitoring application responsible for the alarm. To the right of the timeline, a time series plot is shown, where the system frequency is shown in grey and the frequency in the islanded areas is shown in blue. To the right, voltage phasors for the system and the island are shown (one for each included PMU). In addition, the division of the system into islands is indicated on the single-line diagram, using the same colouring scheme. Disconnected lines are shown in red.

(The three windows to the upper right are always shown in the GUI main window, and thus not specifically related to the alarm.)

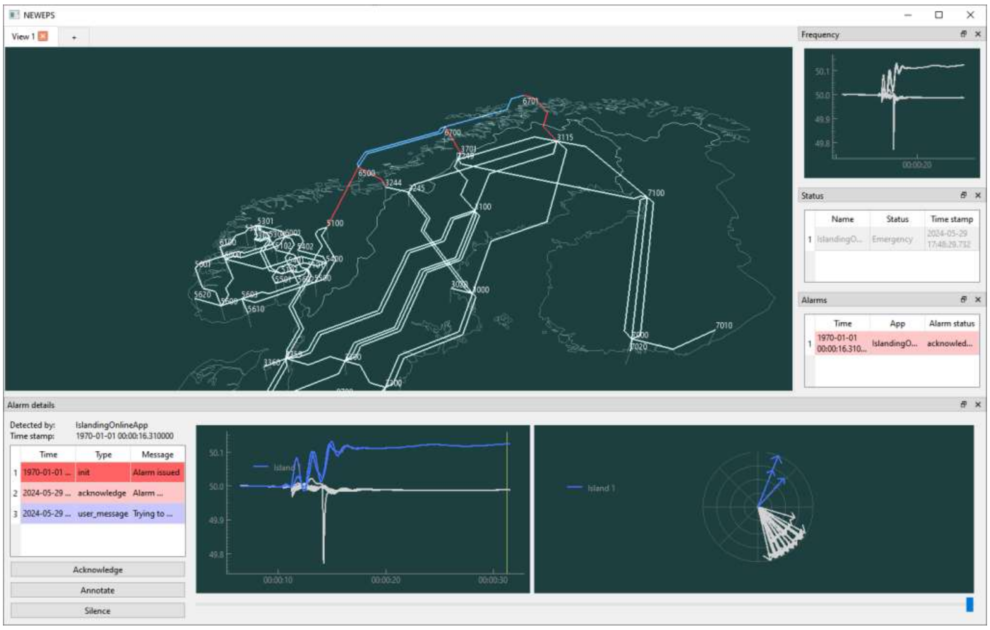

Figure 42: [Alarm view: Islanding]: An alarm view showing detailed information about an islanding alarm.

In a similar way, the alarm view of the oscillation monitoring application is presented in Figure 43. The N4SID application is used to detect the oscillations in this case. To the right of the timeline, three plots are shown, which are the time series plot of the selected frequencies, the mode estimation visualisation of the eigen values on the complex plane, and the corresponding observability mode shapes. The colours in the topographic view are mirrored in the time series plot and the compass plot.

Figure 43: [Alarm view: N4SID]: An alarm view showing detailed information about the oscillation detection.

The voltage stability application raises an alarm, which when opened shows the load voltage and the load current as shown in Figure 44.

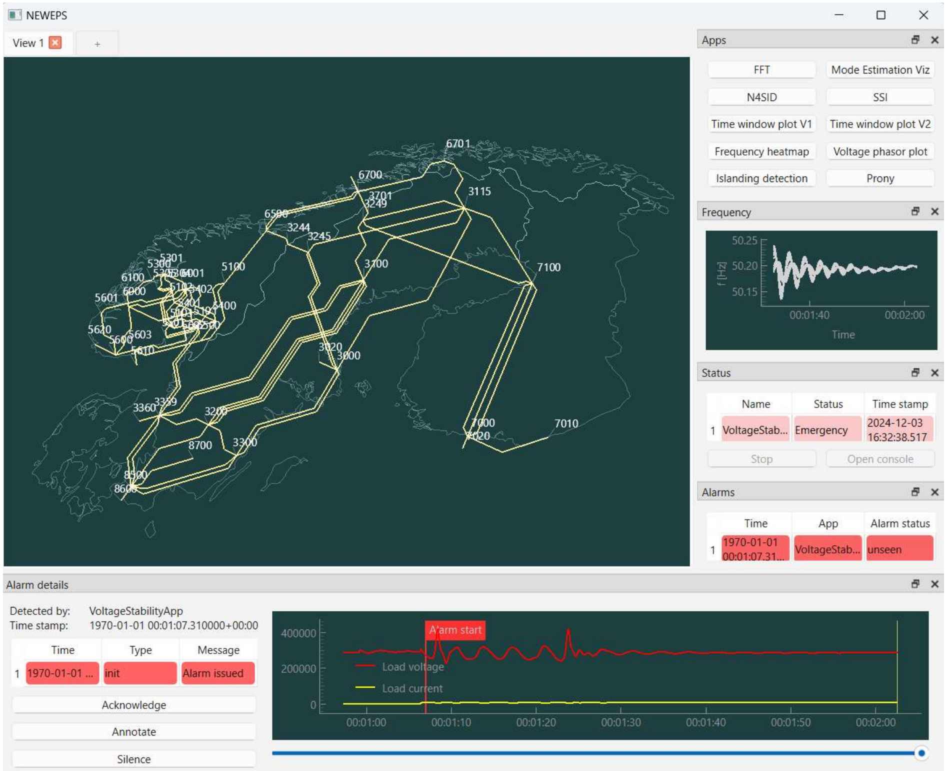

Figure 44: Voltage stability application alarm view showing the load voltage and the load current.

3.6 NEWEPS Test & Demonstration platform laboratory integration

The input to the NEWEPS Test & Demonstration platform is PMU measurements streamed according to the C37.118 standard. The platform has been validated to function with three different PMU data sources: historians from PMUs in the Nordic grid, simulation based emulated PMU data, and laboratory based synthetic PMU data. In the lab, synthetic PMU data can be generated in real time by the TOPS in the Python environment or from an external real time simulator (e.g. OPAL-RT) as shown in Figure 45. Tests of the NEWEPS Test & Demonstration platform has been conducted in a laboratory environment in the NSGL (National Smart Grid Laboratory) in Trondheim. This section first introduces the NSGL and its main features and characteristics. The section continues highlighting how Hardware in the Loop and Power Hardware in the Loop test configuration can be created with integration of synchrophasors and IEDs. Moreover, it is indicated how phasor based real time simulations can be integrated. Finally, the test configuration adapted for the NEWEPS project is described.

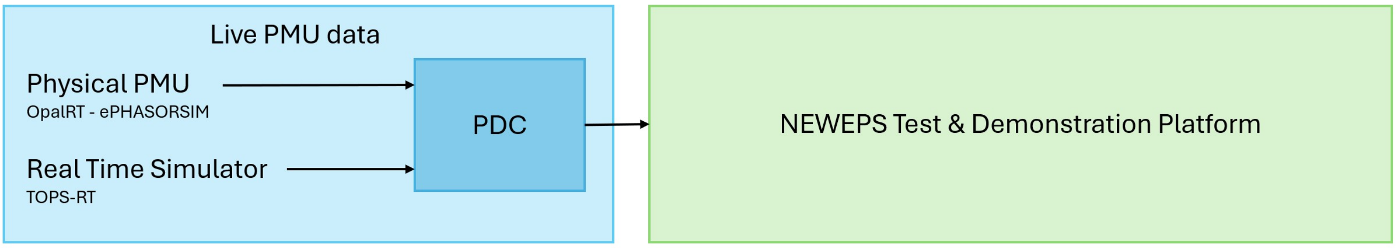

Figure 45: Real time inputs for the NEWEPS platform

3.6.1 The Norwegian National SmartGrid Laboratory

The NSGL is a laboratory facility located in Trondheim, Norway, and jointly operated by NTNU and SINTEF. The facility can accommodate tests in the power range up to 200 kW and the electrical layout has been designed to be easily reconfigurable for offering a high degree of flexibility. The laboratory comprises 5 three-phase ac busbars rated for line-to-line voltages up to 400 V_{RMS}, and 4 dc busbars rated for up to 700 V_{dc}. These bus-bars can be operated independently or interconnected via contactors or cable connections. Inductors can be inserted to introduce series impedance between the busbars for emulation of weak grid conditions. A view of the laboratory infrastructure with its key components is shown in Figure 46.

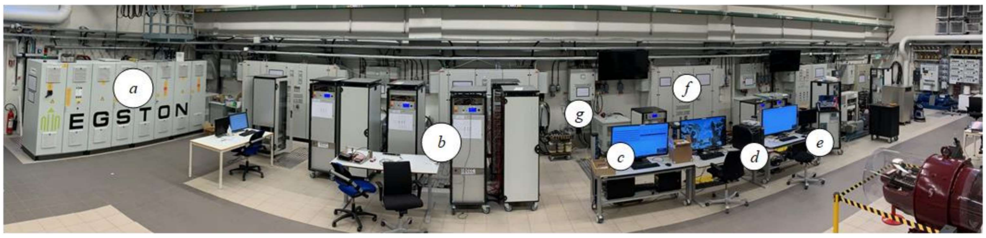

Figure 46: View of the laboratory infrastructure including key components a) power amplifier, b) MMC prototypes, c) PDC, d) Workstations for operating the OPAL-RT real-time simulator, e) MUs and IEDs, f) AC bus and g) DC bus.

A real-time simulation platform consisting of three OPAL-RT targets is available and can be utilised for rapid prototyping of converter controls and/or digital RTS implementation for HiL-tests (Hardware-in-the-Loop). The OPAL-RT targets are also utilised for data logging and communication with industrial protocols. All targets support communication via fibre optic connections.

A 200 kW COMPISO CSU 200 power amplifier from EGSTON Power is installed in the laboratory and offers six controllable outputs with a 5 kHz large signal bandwidth. These outputs can be directly connected to the ac and dc bus bars via a matrix of contactors controlled by a mode selector available in the software control interface for the unit. The COMPISO unit is connected via fibre optic communication to the OPAL-RT targets.

The OPAL-RT units, all converters and the PA are interconnected via a fibre-optic link supporting the Aurora protocol. A local communications network has been created to support communication with most industrial protocols.

The communication network can emulate a system based on the IEC 61850 standard to exchange layer 2 ethernet frames following a publish and subscribe methodology. Additionally, wide area network communications can be emulated to exchange layer 3 packets following IEC 60870-5-104, C37.118 or OPC-UA protocols. The OPAL-RT units can handle IEC61850 standard communications, C37.118, IEC 60870-5-104 and OPC-UA server. The IEDs, the PDC and additional loggers and controllers are interlinked via these protocols. Industrial switches and routers can be configured within a flexible network to carry out different tests with the devices.

Figure 47: Overview of the devices supported in the laboratory: a) RTS, b) PDC interface, c) optic fiber rack, d) IEDs, e) MUs, f) Master Clock, g) LAN switches and WAN routers, h) 2-Level converters with fiber optic communications, i) Linux server and j) current

3.6.2 Control Room Laboratory

A control room laboratory is under development at NTNU with the aim to shorten the gap from research and application developments to real environment prototype implementations. The control room laboratory facilitates to adapt, implement, and test existing or newly developed WAMS applications.

The control room laboratory is primarily used for research, development, and demonstration purposes. It addresses various design challenges related to data communication, storage, and security. The main objective is to test new applications for stability monitoring, with a focus on visualizing stability indicators and wide-area operational data.

The control room laboratory serves as a platform for developing applications and visualisations. It allows the evaluation of design choices such as centralised vs. distributed systems, information management and cybersecurity. The setup includes real-time simulators, PDCs connected to real or simulated PMU data, operator information systems for power grid visualisation, and a Real-Time Automation Controller (RTAC) for control actions. The lab also supports software development for testing visualisations, implementing stability indicators, and experimenting with in-house power system simulators. Fig. 50 shows an overview of the architecture of the Control Room Laboratory at NTNU.

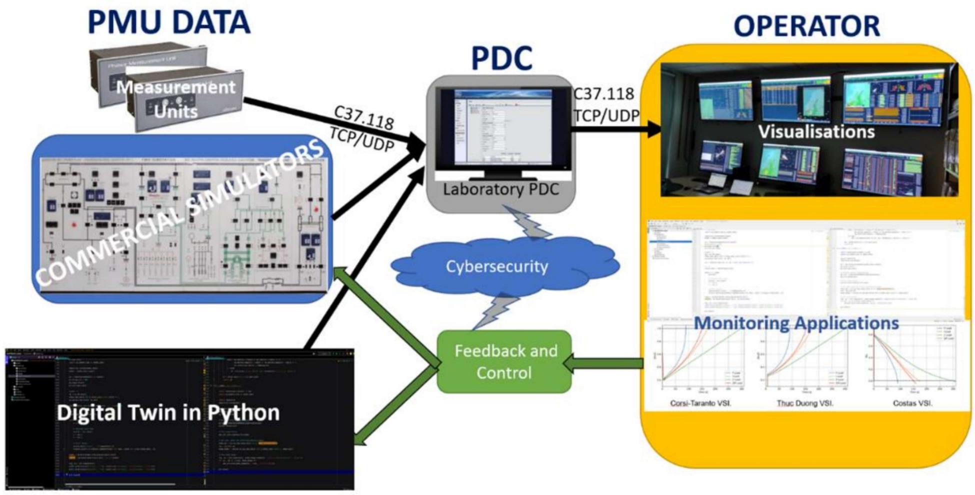

Figure 48: Overview of the architecture of the Control Room Laboratory at NTNU

The setup supports testing with both real-time and simulated data, allowing for realistic large-scale power system models. Additionally, the laboratory could train grid operators on WAMPAC systems, providing valuable feedback for application development. These activities could contribute to developing specifications for real-world implementation thus closing the gap between academic research and industrial deployment.

During the NEWEPS project a few live demos have been hosted by the laboratory to present the platform integration and the visualisation applications.

3.6.3 Integration of phasor real time simulation and synchrophasors in Hardware in the Loop experiments

Control-Hardware-in-the-Loop (C-HiL) testing has become a standard procedure for verifying control functions in complex systems across multiple engineering and research fields. HiL approaches are increasingly being used to validate the performance of power system components under controlled and realistic conditions. Additionally, the rapid advancement of computational capabilities in digital RTS platforms has broadened the scope of applications to include larger and more complex grid models.

Another area of development in HiL methodologies is Power-Hardware-in-the-Loop (P-HiL) testing, which involves connecting actual power hardware to a real-time simulation. The essential technology for P-HiL applications is the power amplifier (PA), which links the real-time simulation with the hardware under test (HUT). Effective P-HiL testing requires both high control bandwidth and significant power capabilities, leading to the recent development of high-performance switch-mode PAs.

3.6.4 Phasor-based and EMT simulation of power systems

Real-time simulations of power systems for P-HiL testing traditionally rely on EMT (electromagnetic transient) models with small time steps, providing the high resolution needed to analyse rapid transient dynamics with a high degree of accuracy and fidelity. EMT models operate in the time domain, allowing for direct interfacing with power amplifiers (PAs) for P-HiL experiments. However, EMT simulations require significant computational resources, and the demands increase more than linearly with the complexity of the simulated power system. To distribute the simulation across multiple processor cores, the models often need to be partitioned. Typically, the time steps range in the tens of microseconds, and a single RTS core can handle only a few dozen buses.

For large power systems, phasor-based models are increasingly favoured for time-domain simulations and have also recently been used in HiL testing. With time steps typically in the range of tens of milliseconds, a single core can simulate thousands of buses. Thus, when the focus is on electromechanical oscillations, sub-synchronous phenomena, or interactions below tens of Hertz, phasor-based methods can provide adequate accuracy while significantly reducing computational costs compared to EMT models. The efficiency gains from using phasor-based simulations can reach up to two orders of magnitude compared to full EMT models.

Figure 49 illustrates a general method for implementing interfaces between a real-time phasor simulation and the hardware under test (HUT) in a P-HiL configuration. These interconnections are based on the ITM (ideal transformer model), with voltage outputs and current feedback adjusted for the stage requiring a longer time step, tailored to specific needs. The voltage at the selected interface node is converted from the phasor domain to an instantaneous sinusoidal waveform via the inverse Park's transform. This instantaneous sinusoidal voltage waveform serves as the reference signal to the PA. Because phasor domain simulations can operate with longer time steps than the PA control, a rate transition mechanism must be included. For instance, a zero-order hold (ZOH) can be implemented that keeps the voltage phasor constant across several time steps. Meanwhile, feedback is processed using a Park transform and a low-pass filter (LPF). Active and reactive powers can be utilised directly as feedback signals to the phasor simulation. Instantaneous three-phase voltages and currents at the HUT interface with the PA are then measured and utilised to calculate active (P) and reactive (Q) power, which are subsequently scaled and fed back into the phasor simulation.

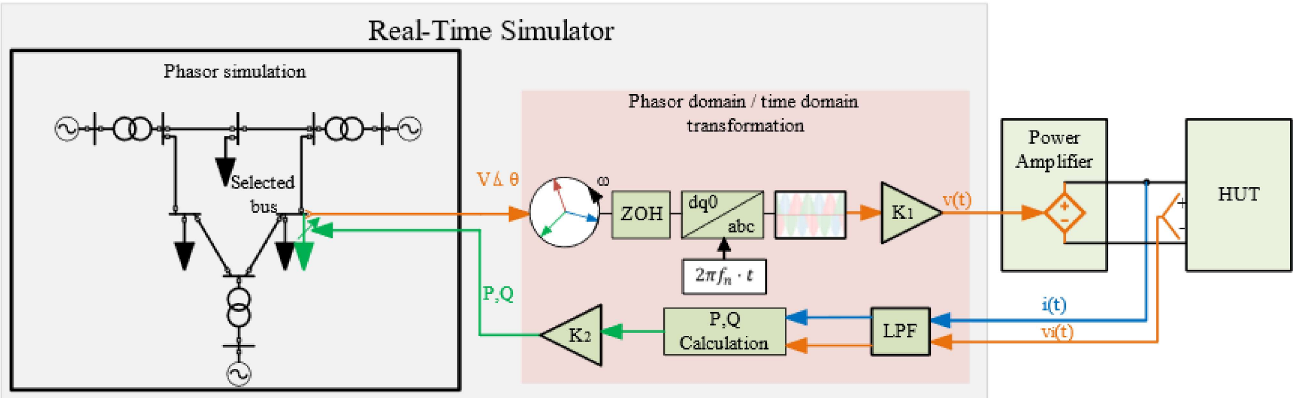

Figure 49: Scheme for integration of phasor simulations in HIL laboratory configurations

3.6.5 Integration of synchrophasors

Synchrophasors can be generated by dedicated PMU devices or through PMU functionalities integrated within Intelligent Electronic Devices (IEDs). Typically, these PMU functions capture instantaneous three-phase values of voltage and current in digital format, adhering to the IEC 61850-9 sampled values (SV) protocol. An analogue voltage and current are digitised and published as SVs by a device known as a merging unit (MU) at the substation. IEDs subscribe to the SVs published by the MU in the digital substation and can subsequently generate synchrophasors. The synchrophasors are aggregated and organised by a PDC, which can then selectively stream them to other devices for additional processing and the implementation of wide-area functionalities.

Figure 50 presents four approaches for integrating synchrophasors and IEDs in P-HiL, each marked with a numerical identifier from 1 to 4, which are briefly outlined below. All methods can generate multiple PMU signals, but the first three must contend with hardware constraints (e.g. maximum sensor count or maximum PMUs supported by each IED). These methods can also be combined in a single experiment when PMU signals from multiple buses are required.

1. First Approach (PA-MU-PDC): In this configuration, RTScontrols the power amplifier (PA) to apply calculated voltages or currents at a designated bus in the simulated model directly to the HUT. These voltages and currents are digitised by the MU, which creates the synchrophasors. The synchrophasors are then streamed to the PDC using the PMU standard protocol C37.118. This setup enables the testing of all measurement effects from the sensors and the digitisation process of the MU.
2. Second Approach (PA-MU-IED-PDC): This approach is similar to the first, as it includes measurements of actual voltages and currents. However, the synchrophasors are generated by an IED that includes PMU functionalities and sent to the PDC following the C37.118 protocol. The IED can digitise the voltages and currents if it has this capability, or they may be digitised by an MU and published as IEC 61850 SVs for the IED to subscribe to. This method is particularly suitable for testing IED functionalities and configuring the IEC 61850-9 SV protocol.
3. Third Approach (RTS-IED-PDC): Here, the RTS directly publishes the IEC 61850 SVs, with the IED subscribing to them. The IED generates the synchrophasors and streams them to the PDC using the C37.118 protocol. This approach is simpler to implement but is appropriate only when the effects of physical measurements are deemed insignificant.
4. Fourth Approach (RTS-PDC): In this case, the RTS directly streams synthetic synchrophasors to the PDC. While this approach is the easiest to implement, it is primarily suitable when the focus is on further processing PMU signals in a WAMPAC application rather than examining the hardware behaviour of IEDs or the communication infrastructure.

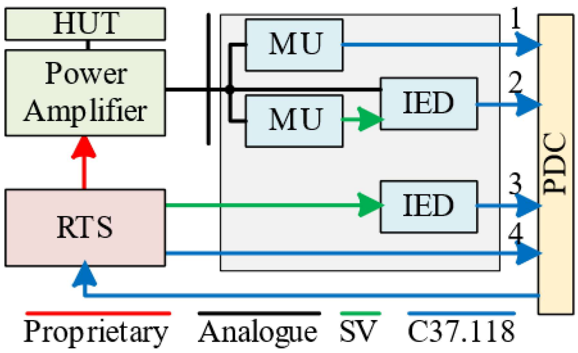

Figure 50: Approaches to integrate synchrophasors in HIL laboratory configurations

3.6.6 Setup for laboratory test of the NEWEPS Test & Demonstration platform

This section describes the laboratory configuration that has been adopted to integrate the NEWEPS Test & Demonstration platform. A Nordic44 model has been utilised, and experimental results have been consistent with offline simulations with the same model. The Nordic 44 system can be simulated with the tool TOPS-RT or with the Real-Time (RT) simulator OPAL-RT. Phasors from the N44 buses can be sent with the protocol C37.118 to a master PDC. Wide-area communications routers have been used in the setup to move phasors network traffic from the master to the client.

A Phasor Data Concentrator (PDC) software gathers the different phasors of the N44. If the user needs to validate physical PMUs with hardware in the loop simulation, the OPAL-RT simulator can publish voltages and currents over the local area network in the form of sampled values according to the IEC61850 standard. It is possible to select a bus voltage and current from the N44 electromechanical-transient model and convert the magnitude and angle of the phasor to three phase instantaneous voltage and current signals. This conversion requires correct synchronisation of the real time simulator to avoid angle drifting in the estimation algorithm of the PMU. If the RT simulator is not synchronised correctly the estimated angle in the PMU could drift, due to its lack of GPS synchronisation.

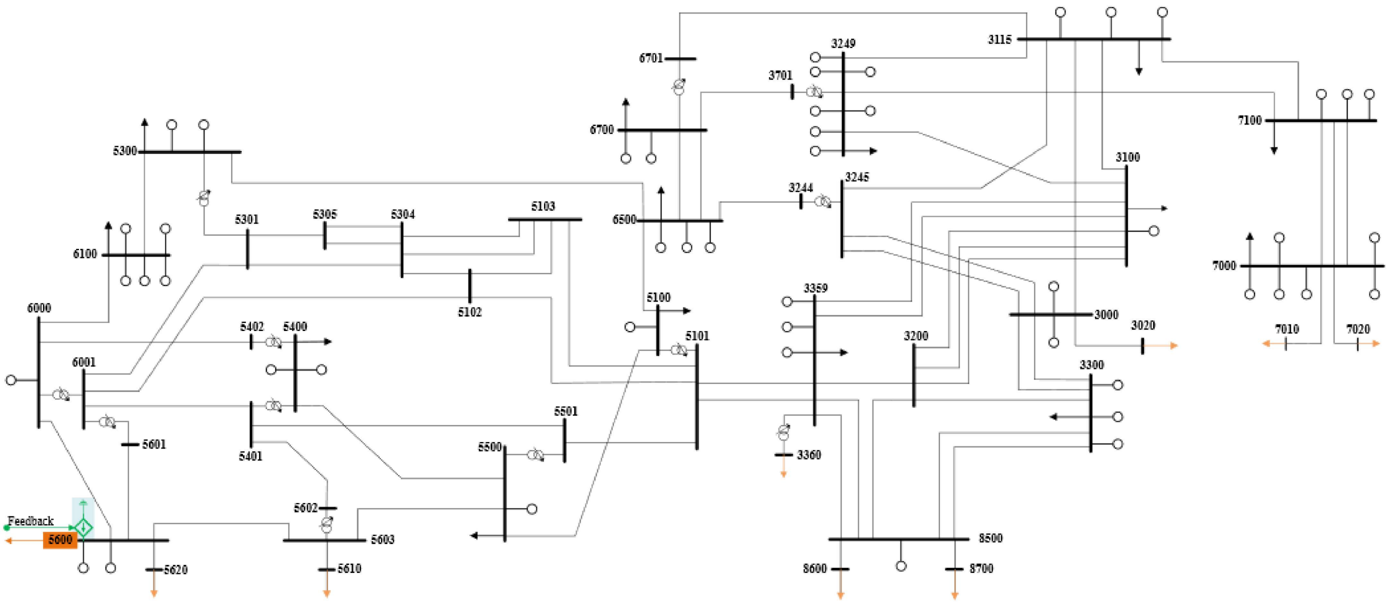

Figure 51: Nordic 44 schematic

RT-LAB is the software used to configure and load the RT simulation of the N44. OPAL-RT hardware is the target device used by RT-LAB to perform the RT simulations. Figure 52 shows RT-LAB software used to configure the N44 RT-simulation. RT-LAB's version is 2024.1.1.38. In the figure it is presented the model *PMU1_modified*. This model is developed in Matlab SIMULINK software and compiled by RT-LAB to be executed in the OPAL-RT simulator. Besides, RT-LAB can configure I/O interfaces used in the OPAL-RT. I/O interfaces application in RT-LAB configures the C37.118 protocol and IEC 61850 sampled values of the OPAL-RT. Additionally, the GPS synchronisation of the OPAL-RT is configured with the I/O interfaces.

Figure 52: RTLAB configuration software

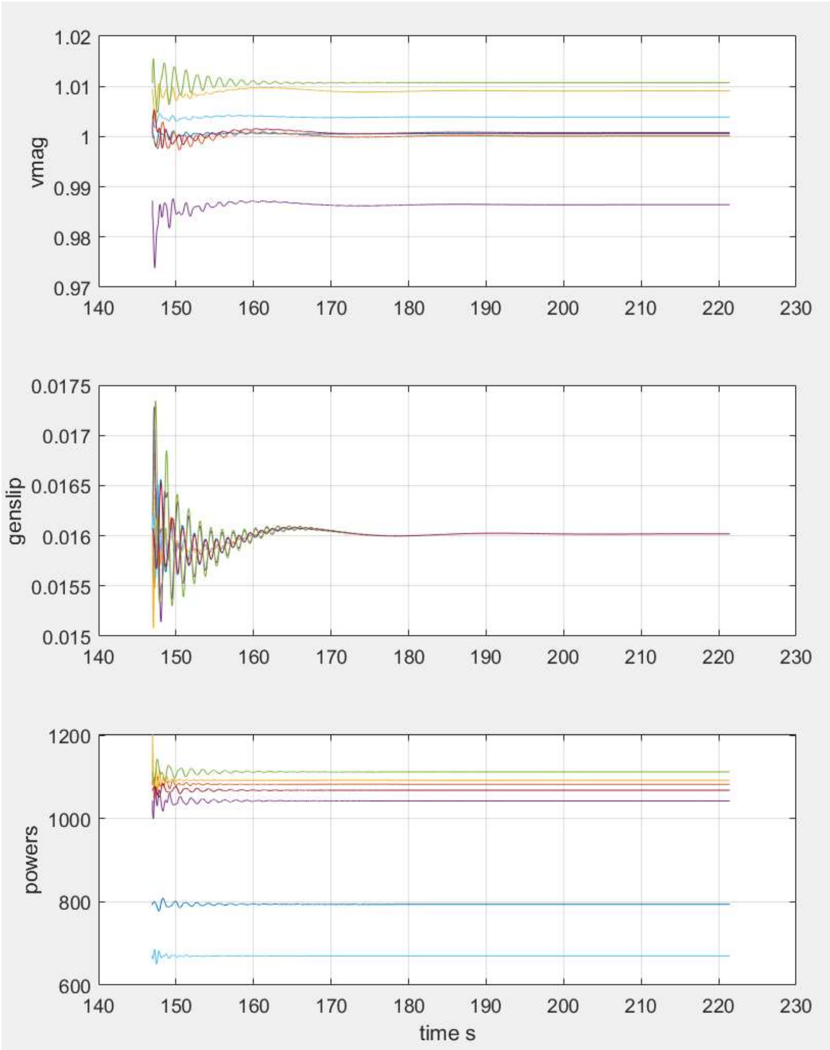

Figure 53: Transient triggered by opening the lines in the Hasle corridor

SEL-5073 phasor data concentrator has been used to gather all the PMUs sent from the N44 in the OPAL-RT. The software uses network time protocol synchronisation available in the personal computer with Windows operating system. The PDC has been configured to connect to all PMUs available from the TOPS-RT software, the OPAL-RT or the mixed OPAL-RT plus physical PMUs. Additionally, the PDC can send the PMUs from the N44 to the NEWEPS Test & Demonstration platform. Figure 54 shows the ABB_PMU and SiemensMUkf physical PMUs connected to the PDC. On the one hand, an example of ABB_PMU has synchronisation quality poor i.e. Fault Time Quality. On the other hand, the physical PMU SiemensMUkf has Time Quality Normal i.e. the PMU has high quality synchronisation below the μs.

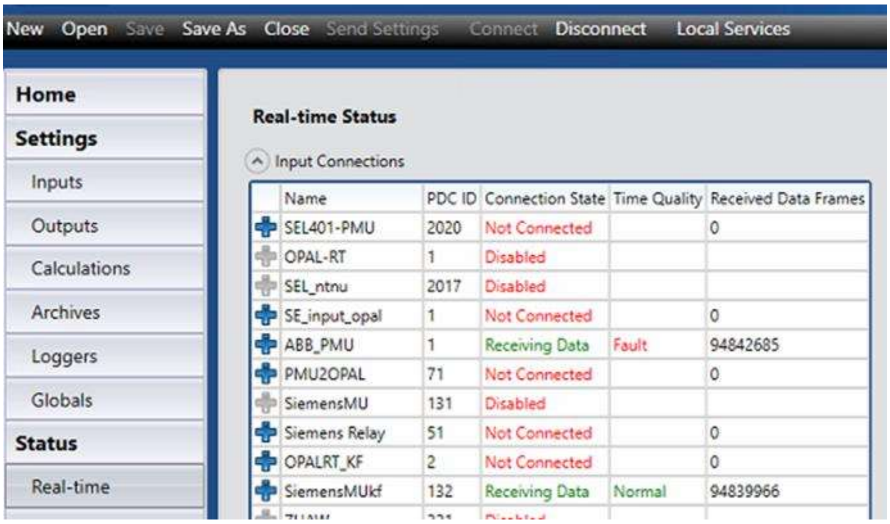

Figure 54: Physical PMUs connected to the PDC.

The satellite synchronised network clock SEL-2488 is used to synchronise with GPS the physical PMUs. The synchronisation follows the IEEE 1588 precision time protocol. The communication switches MOXA PT-7728 used in power system substations run with local area connection to integrate physical PMUs and they handle the SVs traffic from OPAL-RT. The routers used in this setup are Planet IGS-6325-16P4S.

Within the NEWEPS project, the NEWEPS Test & Demonstration platform has been integrated with the laboratory facility and tests conducted to verify that the operation is consistent with the results obtained with offline simulations. Since the integration of the platform is after the PDC, it has been verified that from the functional perspective the differences are rather minimal. The applications in the NEWEPS Test & Demonstration platform operated also similarly to what experienced with offline simulations. This confirms that indeed the NEWEPS Test & Demonstration platform offers sufficient flexibility in operating with different type of input. Moreover, the main difficulties in testing with real hardware lie on the hardware integration, management of the timing signals and generation of the signals directed to the PDC.

3.7 Summary

The NEWEPS Test & Demonstration platform was developed to prototype functionalities of a future Nordic WAMS and WAMPAC system. Using an application-based architecture, it enables testing and demonstration of WAMS and WAMPAC functionalities, including oscillation monitoring, voltage stability, and islanding detection. The platform relies on Kafka for data communication and supports scalability, modularity, and fault tolerance. To enable multiple ways to validate, test and demonstrate various solutions, the NEWEPS Test & Demonstration platform is utilizing a standard-based interface, where input of PMU data streams can be originating from simulations, historians, or on-line measurements.

The platform features a range of visualisation interfaces, to provide relevant and critical alarms and information to the operator. Coordination of information between different applications, as well as between different TSOs, enables increased situational awareness.

The NEWEPS Test & Demonstration platform has been developed iteratively, based on the project learnings regarding architectural perspectives and innovative ways for visualising power system dynamics for the operator, as presented in chapter 2.

The WAMS and WAMPAC applications developed within the project, described in chapters 4 and 5, have been implemented and the NEWEPS Test & Demonstration platform has been utilised for demonstration purposes and for validating the functionality of the applications.

In this way, the NEWEPS Test & Demonstration platform has been able to effectively bridge the gap between research and industrial application.

4 WAMS Applications

4.1 Introduction

As already introduced, utilizing measurements from PMUs enable the possibility of providing the operators more detailed and accurate information about the current operational situation in the grid including identification of the power system dynamic behaviour. There are different dynamic behaviours and stability phenomena that is of interest for the operators, but in the NEWEPS project the focus has been on:

- voltage stability monitoring,
- monitoring and detection of natural oscillations, and
- detection of forced oscillations and resonances.

For these stability phenomena, WAMS applications have been developed, implemented and tested. This chapter include a detailed description of each of the developed applications. The descriptions start with the application requirement of the operators followed by a theoretic summary of the methods used in the development. The verifications and validations performed are also described.

In addition to these applications, a simple frequency-difference based islanding detection application and two oscillation monitoring applications: one based on system identification techniques (N4SID), and one based on Fast Fourier Transform (FFT) are also included in the NEWEPS Test & Development Platform. These applications are not described in detail in this chapter but are instead presented in section 3.5.

4.1.1 Application test methods

There are various ways in which applications developed can be tested and verified, and the following methods have been utilised in the NEWEPS projects:

- Code validation tests.
- Application tests using manually made input signals.
- Application tests using historical PMU measurements as input signals.
- Application tests using input signals created based on dynamic power system simulations.

The different methods have different strengths and purposes and complement each other.

Code validation tests are performed to ensure that the scripts/tools behave correctly and generate outputs as expected. Code validation was performed continuously in parallel with the code development in the project.

Application tests using manually made input signals have been used to compare the application outputs to a theoretically known answer. For the oscillation monitoring application input signals were created using a step on a small model created to have defined oscillation modes.

Application tests using historical PMU measurements as input signals is an excellent way to test the application output when it is fed with real input signals, including noise, potential bad data etc. The drawback with this method is that all information of the operational situation is not known, why the results can only be evaluated as realistic or not since the theoretically correct result are not known.

Application tests using input signals created based on dynamic power system simulations provides a complement to using measurements, since the operational situations behind these signals are known and can be created as desired. This provides possibilities to compare how the result of the applications changes, for example due to different levels or types of noise. It also provides the possibility to study potential variances in the result due to different operational situations with known differences. This method also makes it possible to test the applications in more extreme situations than from which historical real time data are available and to study potential future scenarios. Additional tests like for example how the results differ with number of PMUs (input signals), location of PMUs, as well as various forms of bad data testing have also been performed.

In this project, tests input signals were created using the PSS/E simulation tool and the Python-based open-source simulator TOPS. Both simulators have implemented the commonly used aggregated Nordic 44 model, while PSS/E has also utilised the full planning model from Svenska kraftnät. Various operational situations and disturbances have been used in the testing.

Test & Validation Methodology

In this work, five levels have been used to test and validate the applications:

- **Level 0:** Validate algorithms against theory, done in the theoretical development phase.
- **Level 1:** Validate algorithms with known answers (e.g., using linearised models).
- **Level 2:** Validate algorithms with reasonable results (e.g., quantified instability margins or other assessment of time-domain results).
- **Level 3:** Validate algorithm functionality with different levels of available data (e.g., levels of PMU coverage).
- **Level 4:** Validate algorithm functionality with faulted data (e.g., errors in PMU data such as missing data, time shifts, and incorrect amplitude).

4.2 Voltage stabilty monitoring

This section describes the development of methods allowing early detection of voltage instability and risk of voltage collapse. Appropriate control actions allowing preventing the identified voltage problems is also discussed.

4.2.1 Introduction

When it comes to voltage stability monitoring, there are several specific voltage stability related issues that could be addressed. There are also a number of already existing applications for voltage stability monitoring, both model-based and pure measurement based. An important initial activity, therefore, has been to assess and compare existing methods and based on the assessment identify the need for further development and more research.

The focus in this project has been on measurement-based applications for online monitoring and detection of voltage instability. Additionally, the algorithms provide information about the margin to maximum load or power transfer that will lead to instability.

New and improved applications were developed and analysed by computer simulation studies. The applied research methods include numerical validation in an extended real-time simulated environment and experimental testing with recorded measurements from the Nordic power grid. Eventually, the most promising methods have been implemented for prototyping in the NEWEPS Test & Development platform

Visualisation approaches related to the new applications have also been developed and demonstrated.

4.2.2 Voltage stability application requirements for an operator

Two main use cases related to voltage stability assessment are most relevant for operators:

- Detection and mitigation.
- Contingency/look-ahead analysis.

Here, the main focus for the application development has been online detection and mitigation, but some comments regarding contingency analysis and look-ahead are included to cover the whole picture in operation.

Detection and mitigation

Main requirements for operators:

- Detect critical operating situations as early as possible.
- Provide estimates of margins to voltage instability in terms of maximum power transfer or loadability.
- Get early warnings (alerts) and alarms based on the actual operation situation with short time delays.
- Ability to get more information by quick and easy understandable visualisations.
- Get decision support in terms of where to take corrective actions, which actions and the extent (amount of load shedding, reactive compensation, etc.).
- Decisions on available automatic controls and System Integrity Protection Schemes (SIPS) that should be immediately armed.

Contingency/look-ahead analysis

Operators are equipped with SCADA/EMS functions to monitor and enforce operational security limits, e.g., based on the N-1 criterion. Available voltage stability assessment tools (VSA tools) should be combined with online indicators to enhance the look ahead analysis. See additional descriptions on the integration between contingency analysis, security assessment, and corrective actions in chapter 5.

Possible requirements for operators:

- Practical integration of the online indicators with the state estimator and VSA tools within EMS.
- Detect critical post contingency operating situations.
- Provide estimates of post contingency margins to voltage instability in terms of maximum power transfer or loadability.
- Get early warnings (alerts) based on the most recent operation situation with short time delays.
- Ability to get more information by quick and easy understandable visualisations.
- Get decision support in terms of where to take preventive actions, which actions and the extent.
- Decisions on available automatic controls and SIPS that should be armed.

4.2.3 Stability theory and Methods

Voltage instability is closely related to load dynamics and deficit of reactive power reserves following contingencies like line outages, loss of reactive compensation or critical increase in load demand. There are a considerable number of components in operation, whose dynamic response to the disturbance can compromise the voltage stability in the area in case the voltage regulation capability is insufficient. With increased levels of inverter-based resources connected, this continues to be a relevant problem.

Some of the operating conditions or phenomena that may lead to voltage instability are:

- Voltage instability caused by immediate reactive power imbalance following contingencies.
- Voltage degradation due to angle separation following a contingency.
- Small disturbance voltage stability due to excessive load demand.
- Voltage volatility in the system due to fast dynamic – transient voltage instability.

The literature related to measurement-based Voltage Stability Indices (VSIs) suited for real-time monitoring of voltage stability is extensive. Given that these types of VSIs do not depend on state estimators nor on the knowledge of the full power system model, which could lead to convergence issues near instability scenarios and to the associated rise in computation time and effort, they are able to estimate voltage stability margins considering the current state of the system and detect instability events as they unfold.

Many of these VSIs focus on the estimation of Thévenin parameters (voltage and impedance phasors) of the system for voltage stability assessment. A well-known index that is based on such principle is the AD (Adaptive Method), presented in [42], which proposes an adaptive method to estimate the Thévenin parameters. Another example is the AA (Adaptive Approach), proposed in [43], which presents an adjustment based on sensitivity equations for the AD so that it can be used for a wider range of loading conditions. For these VSIs, the system is considered stable if the absolute value of the Thévenin impedance (Z_{th}) is lower than the absolute value of the load impedance (Z_L) obtained from the PMU measurements. However, if Z_{th} becomes equal or bigger than Z_L, it can be stated that the system is in a voltage instability scenario.

Other VSIs focus on sensitivities to define whether the system is stable or not from a voltage stability perspective. In [44], the SZI (S-Z sensitivity Indicator) is defined using the ratio of variations of the absolute value of the apparent power of the load (ΔS_L) and the load impedance (ΔZ_L). For this VSI, a negative value during a load increase scenario means that the system is providing the required load demand, i.e., the system is considered stable. On the other hand, a positive value during a load increase scenario means that the system is not meeting the load demand, and it is, therefore, unstable. Although the SZI is sensitivity-based, it is also possible to estimate Thévenin parameters from this VSI and, in such cases, the voltage stability conditions are the same as defined previously for the AD and AA.

Another example of VSI based on sensitivities is the NLI (New LIVES Index), proposed in [45]. This VSI is defined as the ratio of variations of the active power (ΔP) and the conductance (ΔG). The main concept of this method is that, for a continuous increase in conductance, the NLI will remain positive up to the maximum power transfer condition and become negative past this point. Thus, during a voltage instability scenario, the NLI will have a negative value.

An alternative way of defining the voltage stability condition is to estimate the maximum active power associated to each VSI, since this value provides a direct assessment of voltage stability margins: if maximum active power is higher than the load power, the system is necessarily voltage-stable; and if maximum active power is lower than the load power, the system is necessarily voltage-unstable. Thus, the point where these parameters become equal to each other can be regarded as a point of maximum power transfer (PMPT). Displaying the VSIs in terms of active power is a straightforward approach to help control center operators decide not only whether load shedding procedures should be executed, but also how much load needs to be shed at a time. Table 4 summarises the characteristics of each VSIs, along with their respective method of estimating maximum active power.

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[42] S. Corsi and G. N. Taranto, "A real-time voltage instability identification algorithm based on local phasor measurements," IEEE Transactions on Power Systems, vol. 23, no. 3, pp. 1271–1279, Aug. 2008

[43] D. Osipov, A. F. Ferreira, and G. N. Taranto, "Application of Th´evenin equivalent sensitivity equations for reliable voltage stability assessment," Electric Power Systems Research, vol. 211, p. 108424, Oct. 2022

[44] D. T. Duong, "Online Voltage Stability Monitoring and Coordinated Secondary Voltage Control," Doctoral thesis, NTNU, 2016

[45] C. D. Vournas, C. Lambrou, and P. Mandoulidis, "Voltage stability mon itoring from a transmission bus PMU," IEEE Transactions on Power Systems, vol. 32, no. 4, pp. 3266–3274, Jul. 2017

Table 4: Voltage Stability Indices, their characteristics and way to estimate maximum active power

VSI	Voltage Stability Condition	Maximum Active Power
AD	$AD = \frac{Z_{th}}{Z_L} < 1$	Estimated straight from Thévenin parameters
AA	$AA = \frac{Z_{th}}{Z_L} < 1$	Estimated straight from Thévenin parameters
SZI	$SZI = \frac{dS_L}{dZ_L} < 0$ or $SZI_{th} = \frac{Z_{th}}{Z_L} < 1$	Estimated straight from Thévenin parameters
NLI	$NLI = \frac{\Delta P}{\Delta G} > 0$	Estimated using an interpolation function

4.2.4 Main Results and Developments

Research work towards the analysis and development of real-time voltage stability indicators comprised several case studies: from different types of load modelling and line disconnection events to changes in the placement of monitoring device and presence of noise in the measurements. In this regard, a comparative study was conducted in [46], where findings indicated the need for further investigation in larger test system. This need was tackled in [47] through multiple benchmark networks, including the IEEE 39-bus test system. Another important aspect that has been considered is the impact of regulating and limiter devices often present in more complex and realistic power grids.

Therefore, the focus of this section is placed on simulation results where the performances of three VSIs (AA, SZI_{th} and NLI) are compared and contrasted in terms of voltage stability margin and PMPT estimations. The tests conducted refer to the continuous increase in demand for all loads within the 10-bus network presented in [48], creating a scenario conducive to voltage instability conditions. VSI accuracy was also assessed considering the impact of on-load tap changer (OLTC) transformer operation and generator over-excitation limiter (OEL) actions, including two different ways of dynamically presenting the information provided by each indicator [49].

The 10-bus network contains two generators with operative OELs and one OLTC transformer acting towards correcting deviations from the target voltage of the monitored load bus. The continuous increase in demand leads to consecutive OLTC tap changing operations starting from 90 s of simulation, in an effort to maintain the desired voltage level at the regulated point. This action takes place until 204 s of simulation, when the OLTC reaches its limits and no further tap changing operations are possible.

Moreover, this scenario of progressively heavier loading triggers the field current restricting action of the OELs pertaining to both generators at different time instants of the simulation. Due to these dynamics, the system is inevitably driven to voltage instability and the PMPT is reached at about 412 s – i.e., as soon as the monitored load bus gets to 3206 MW (black vertical dashed line).

Results obtained from the AA method are displayed in Figure 55. The influence of OLTC tap operations on the voltage stability margin is more clearly discernible in the maximum active power value curve (red) when compared to the VSI curve (purple). Changes in the time-varying trends of both curves observed at around

[46] V. M. De Souza, H. R. De Brito and K. O. Uhlen, "Comparison of Voltage Stability Indices Based on Synchronised PMU Measurements," 2023 International Conference on Smart Energy Systems and Technologies (SEST), Mugla, Turkiye, 2023, pp. 1-6

[47] V. M. De Souza, H. R. De Brito and K. O. Uhlen, "Comparative analysis of online voltage stability indices based on synchronised PMU measurements," Sustainable Energy, Grids and Networks, Volume 40, 2024, 101544, ISSN 2352-4677

[48] C. W. Taylor, Power System Voltage Stability. McGraw-Hill, 1994

[49] V. M. de Souza, H. R. de Brito and K. O. Uhlen, "Performance Assessment of Voltage Stability Indices for Real-Time Power Margin Estimation," 2024 International Conference on Smart Energy Systems and Technologies (SEST), Torino, Italy, 2024, pp. 1-6

370 s are a direct result of the triggering of generator OELs. The net effect of including both OLTC and OEL dynamics is a delay in PMPT detection (i.e. when the VSI curve exceeds 1.0) of more than 20 s.

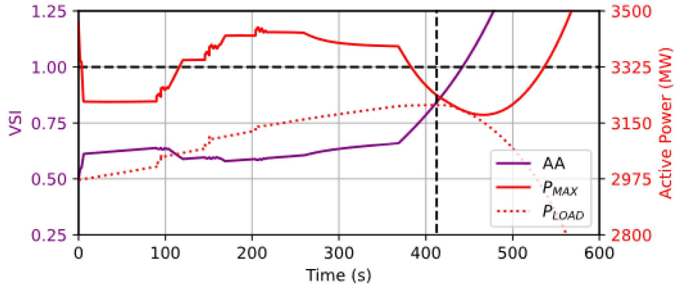

Figure 55: VSI of the AA method and its estimated maximum active power

Results from the SZI_{th} method are shown in Figure 56. Similar to what was discussed for the AA method, OLTC tapping affects the estimation of voltage stability margins. In this case, however, deviations registered in the VSI (green), and maximum active power (red) are considerably greater than observed with the AA method. Nonetheless, the SZI_{th} delay in PMPT identification (i.e. when the VSI curve exceeds 1.0) is of comparable magnitude, as it also exceeds 20 s.

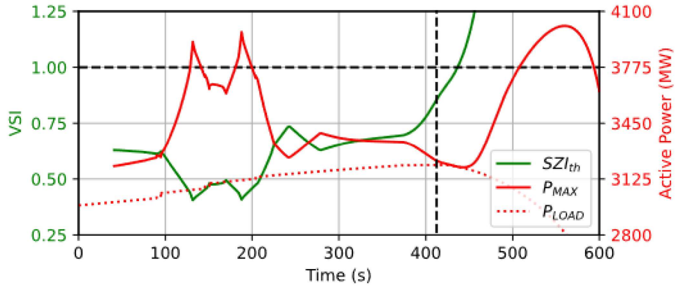

Figure 56: VSI of the SZI method and its estimated maximum active power

Finally, results derived from the NLI method are presented in Figure 57. Following the same pattern discerned previously, OLTC and OEL actions compromise PMPT detection (i.e. when the VSI curve falls below 0.0) by bringing about a delay of 25 s. However, unlike other results obtained for this demand increase scenario, the maximum power estimation curve (red) follows a trend of being very close or even lower than the load active power (P_LOAD) during the period of consecutive OLTC tap operations. This behaviour exemplifies how the use of an interpolation function for maximum active power estimation can potentially lead to erroneous conclusions concerning the dynamic proximity to a voltage instability situation. After 300 s of simulation, such estimation improves, and it is possible to notice the expected downwards trend as a reaction to the triggering of the OELs.

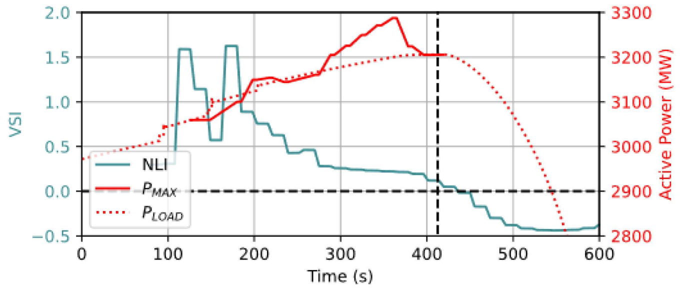

Figure 57: VSI of the NLI method and its maximum active power estimation

4.2.5 Verification and testing with recorded PMU data

Based on the comparative analyses and performance assessments of the previously described VSIs, all conducted within the framework of the NEWEPS project, the SZI was further developed and tested thoroughly considering different scenarios and power systems. The proposed modifications are mainly intended to improve the SZI performance vis-à-vis network reconfiguration events and operation of regulating devices.

The performance of this improved VSI is hereby exemplified using PMU measurements from a real event that occurred in the Nordic grid in January 2022. Similar to the original SZI, this new version is also better suited for long-term stability events, given its formulation characteristics. Therefore, this is a demanding scenario since all events unfold within one minute.

The voltage magnitude behaviour of this event is depicted in Figure 58. As indicated in the figure, between 03:02:00 and 03:03:00 hrs, two transmission lines tripped due to extreme weather conditions, resulting in significantly reduced transfer capacity between two areas. The weakened grid led to a voltage collapse following a short period of oscillations at around 03:03:15 hrs. Subsequently, a grid separation occurred leading to load shedding actions.

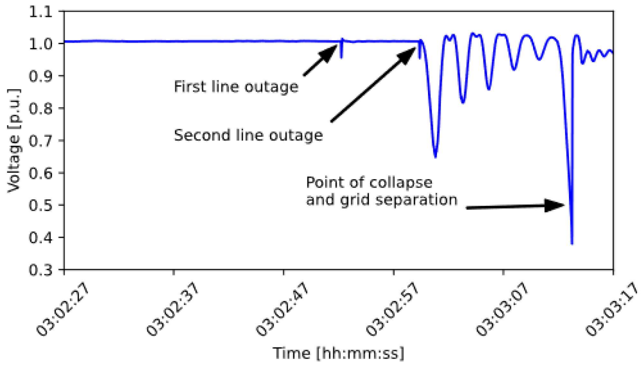

Figure 58: Measured voltage magnitude at a substation.

The ratio of Z_{th}/Z_L over time obtained from the new SZI can be visualised in Figure 59. A red dashed line is included in the figure to indicate the voltage stability limit (unit value). It can be noticed that, after the first line outage, there is a small increase in the value of Z_{th}/Z_L, which translates to a decrease in the voltage stability margins. However, right after the second line outage, the value of Z_{th}/Z_L increases rapidly and exceeds the value of the voltage stability limit for the first time, indicating that a voltage instability event is happening.

In order to avoid grid separation, fast automatic control actions would be needed in addition to the voltage stability monitoring. Considering the time difference between the first time the Z_{th}/Z_L crosses the voltage stability limit and the point of collapse and grid separation for this particular event, a time window of around 14 s would be available for such actions to be implemented. This is an approximate timespan which is specific to the described network conditions, yet it is indicative of the merits of the application.

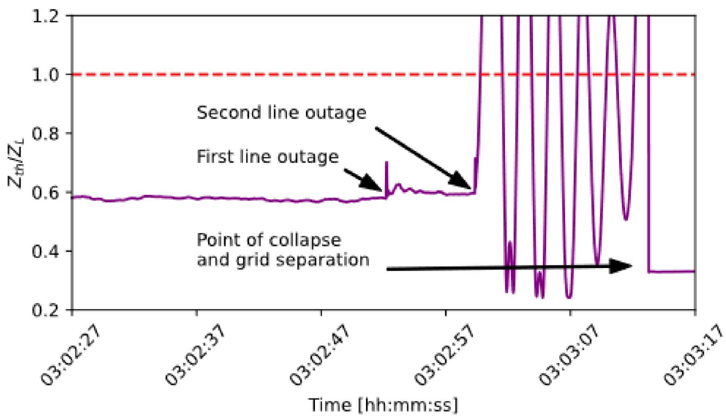

Figure 59: VSI of the SZI method in relation to time, for the voltage instability scenario in the Nordic Grid.

Additionally, the information provided by the modified SZI can also be visualised as displayed in Figure 60. The voltage stability limit is again indicated by a red dashed line. However, as previously defined, instability occurs when the dot goes from a negative value to a positive one. A set of usual curves for the point of monitoring is included as black dashed lines. The continuous black line is updated constantly to provide a better estimation of the system state, as well as the values of load active power in the x-axis. Three distinct time instants represented by the dots are included in Figure 60. This shows how quickly the VSI goes from a normal state of operation to a voltage instability scenario.

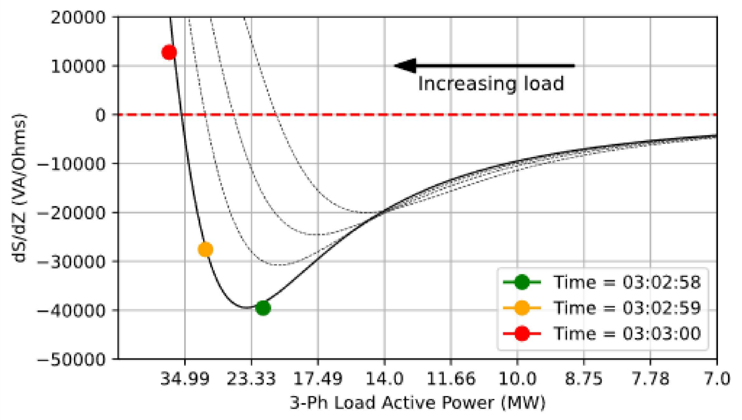

Figure 60: VSI of the SZI method in relation to the load power, for the voltage instability scenario in the Nordic Grid.

4.2.6 Application validation using the NEWEPS Test & Demonstration platform

As described in 4.1.1, a method applied was to test the applications by using PMU data files created based on dynamic power system simulations. The main value from this work is to base the validation on scenarios which are difficult to find from measurements of the real system, e.g., occurrence of instability, extreme events, and future scenarios of demand and production behaviour.

In this work we have utilised the PSS/E simulation software together with Python code to emulate PMU measurements which are then processed by the NEWEPS Test & Demonstration platform to test and validate the WAM modules.

Table 5: List of simulation test cases presented in this report.

Case	Model	Comment
B1	N44	Continuous linear load increase
B2	N44	Continuous linear load increase with white noise applied until voltage collapse
B3	N44	Fairly linear load increase applied as random walk until voltage collapse
E1	Svk	Very limited fairly linear load increase applied as random walk at buss A
E2	Svk	Linear load increase applied at buss A until voltage collapse
E3	Svk	Very limited fairly linear load increase applied as random walk at buss B
E4	Svk	Linear load increase applied at buss B until voltage collapse
E5	Svk	Very limited fairly linear load increase applied as random walk at buss C
E6	Svk	Linear load increase applied at buss C until voltage collapse

Here, the voltage stability indicators implemented in the NEWEPS Test & Demonstration platform (AD, AA, and SZI) have been studied through a large number of test cases, in this report only a few of these are presented. The cases presented are listed in the table below and are further described in text. Simulations are performed using the Nordic44 test system[50] and a Swedish planning model[51] provided by Svenska kraftnät. In this chapter these simulation models are referred to as “N44” and Svenska kraftnät (Svk).

Cases B (using N44 model) and E (using Svenska kraftnät model) are used for the validation of the voltage instability monitoring application. The purpose of these test cases is to evaluate how well the voltage instability indicator functions and how well the distance to instability, in form of maximum power capacity, can be estimated.

- Cases B1 to B3: simulated load increase[52], until reaching voltage collapse, in the N44 model applying different type of noise[53] to the load.
    - Goal: evaluate voltage instability indicator and distance to instability estimation for different type of noise, validated by identified instability levels from time domain simulations.
- Cases E1, E3, and E5: simulated fairly constant load in the Svenska kraftnät model, with applied noise[54] to the load, for three separate buses.
    - Goal: evaluate voltage instability indicator and distance to instability estimation for cases which are not close to instability.
- Cases E2, E4, and E6: simulated load increase, until reaching voltage collapse, in the Svenska kraftnät model, for three separate buses.
    - Goal: validate application results for Cases E1, E3, and E5.

These tests are based on assessment of the theoretical maximum loadability level. Assuming that it is possible to estimate the maximum loadability of a certain bus in the power system, through increasing the demand at that bus above the threshold where the impedance of the demand and the Thevenin impedance of the rest of the system are equal, where tipping point of voltage instability occurs (i.e., tip of the PV-curve).

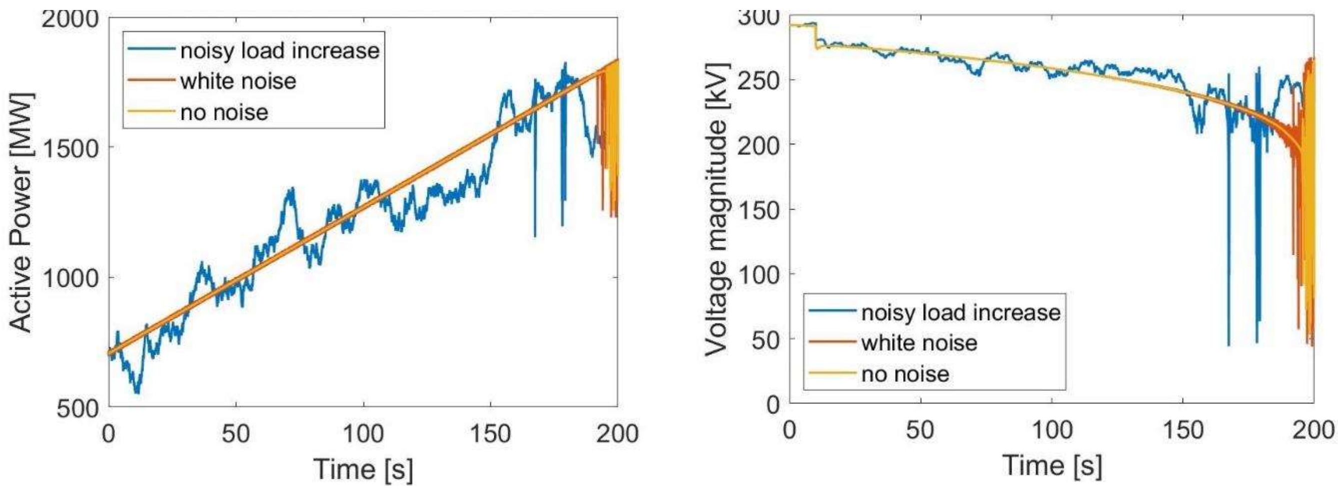

Figure 61: Time domain simulation results for Case B1 (yellow) Case B2 (Red) Case B3 (Blue), presenting active power load and bus voltage magnitude of the studied bus.

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[50] An aggregated model of the Nordic power system containing 44 buses.

[51] Planning model containing over 4700 buses.

[52] Applied to the load on bus 5610.

[53] Noise types include white noise and a random walk function.

[54] Noise is modeled using a random walk function.

The study started using the Nordic 44 model, with cases B1-B3. Figure 61 presents the active power load and bus voltage magnitude at the studied bus during the simulation time. In Figure 62, the bus voltage magnitude is presented as a function of the active power load (the so called “PV”- or nose-curve), used to identify the maximum loadability of the bus.

Studying the bus voltage magnitude, a steep decrease is seen after 10 s when one feeding line was disconnected. The voltage then continues to decrease continuously as a result of the continuous load increase applied to the load connected to the bus. Voltage instability is reached after about 195 s.

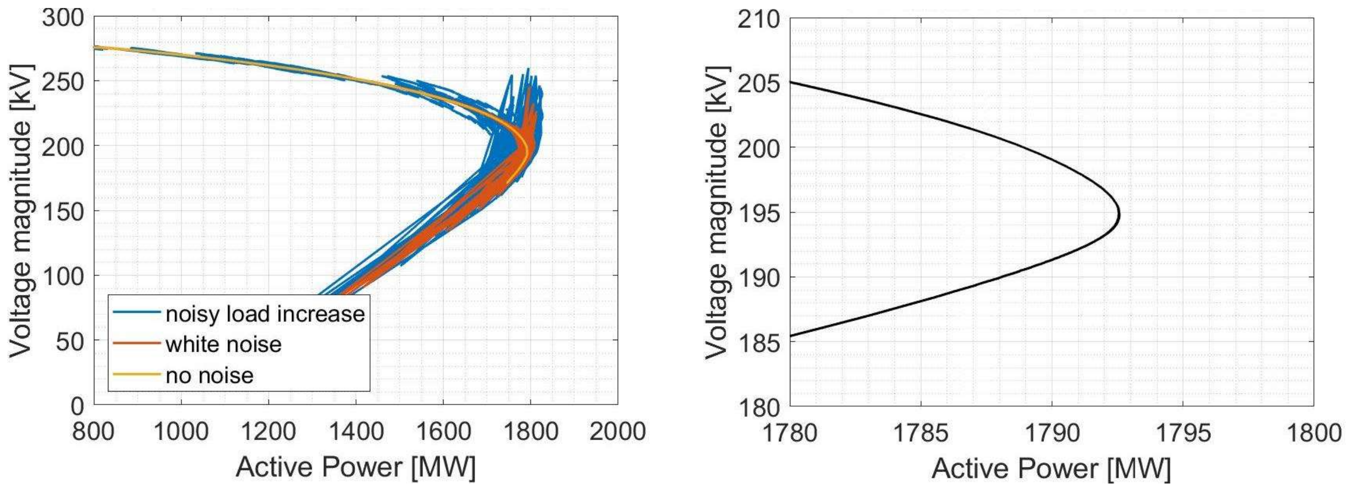

Figure 62 PV-curve from time domain simulation, for Case B1 (yellow) Case B2 (Red) Case B3 (Blue) of the studied bus. Right side shows a zoomed view of the tip of the curve for Case B1.

Before the instability is a fact, the voltage decrease shifts from a linear slope to a more exponential shape indicating it is getting closer to its tipping point. From Figure 62, the conclusion can be drawn that the tipping point occurs when the voltage decreases to about 195 kV and the maximum loadability of the bus is approximately1793 MW.

Figure 63 illustrates the voltage monitoring application results, where the three Voltage stability indicators (AD, AA, SZI) are shown to the left and the approximated maximum loadability to the right.

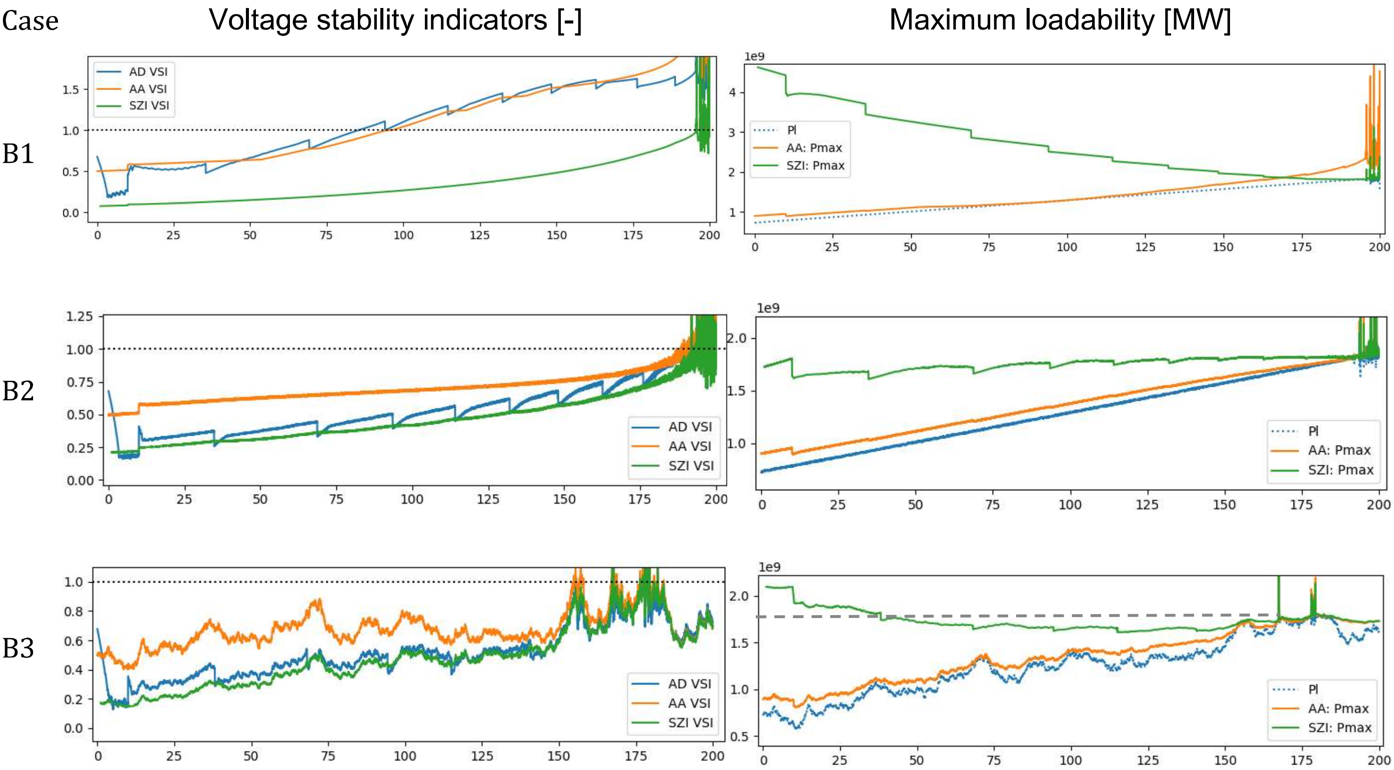

Figure 63 Voltage stability application results for Case B1, B2 & B3, each with three different indicators (left) where >1.0 means instability, and approximated maximum loadability (right) where the dashed blue curve, Pl, is the actual load from the time domain simulations.

It should be noted that the voltage monitoring applications require variations in the load to function. Also, the results depend on initialisation and the swiftness (or ramp rate) of the load change.

From the results presented in Figure 63, it is noted that the indicator SZI is able to identify the voltage instability instant rather correctly for all three study cases. There is however a clear difference between the estimated maximum loadability for cases B1 (no noise) and B2 (white noise), B3 (random walk). In cases B1 and B2, none of the indicators are able to provide reliable estimates ahead of time. While in case B3 the initial estimate of the SZI indicator (after the line trip at t=10s) is rather close to the actual maximum loadability.

The results of the SZI indicator in case B3 leads to the hypothesis of the capacity to provide rough estimates of the maximum loadability ahead of time, depending on the behaviour of the load change.

To test this hypothesis, additional studies were conducted using the Svenska kraftnät model for cases E1 - E6. Here, three different load buses were studied separately based on two scenarios: only noise applied to the load (cases E1, E3, and E5), and load increase without noise (Cases E2, E4, and E6). The previous cases were used to test the hypothesis, and the latter cases were used for verification of the loadability levels for each specific bus. In the studied cases, several grid modifications (disconnection of lines and generators) were implemented to weaken the grid at the studied load bus.

Results from these cases are presented in Figure 64 to Figure 69. For case E1 and E2, presented in Figure 64 and Figure 65, the results show rather good estimation of the loadability for the entire studied period of time. This is however not the case for the other studied cases. Thus, the hypothesis cannot be verified.

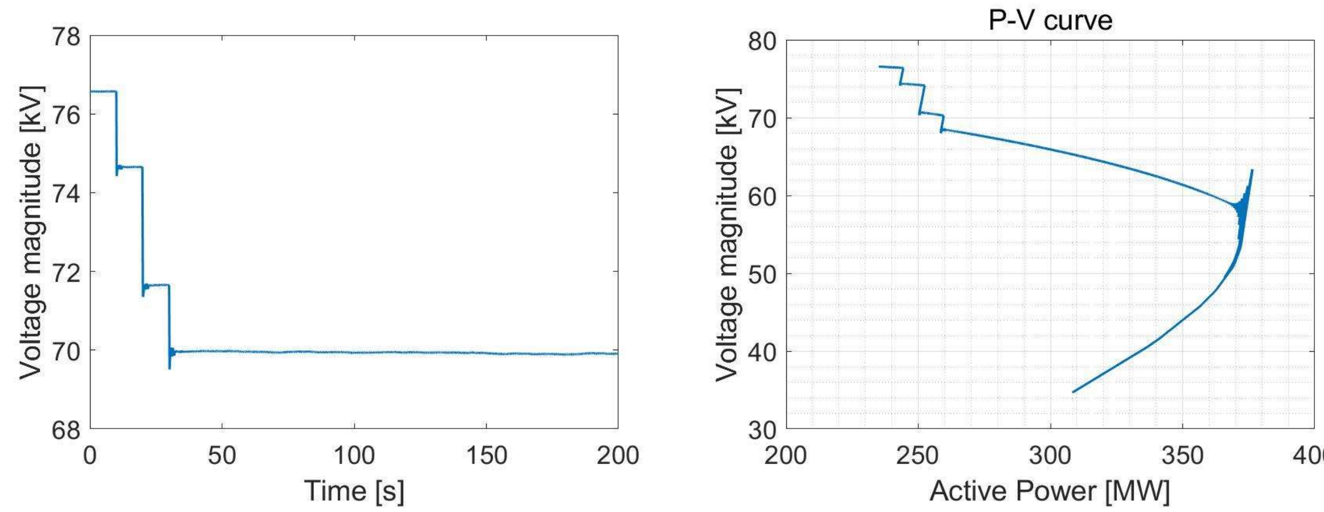

Figure 64 Time domain results for Case E1 (left) presenting the bus voltage at bus A, and Case E2 (right) with the maximum loadability in form of the PV-curve

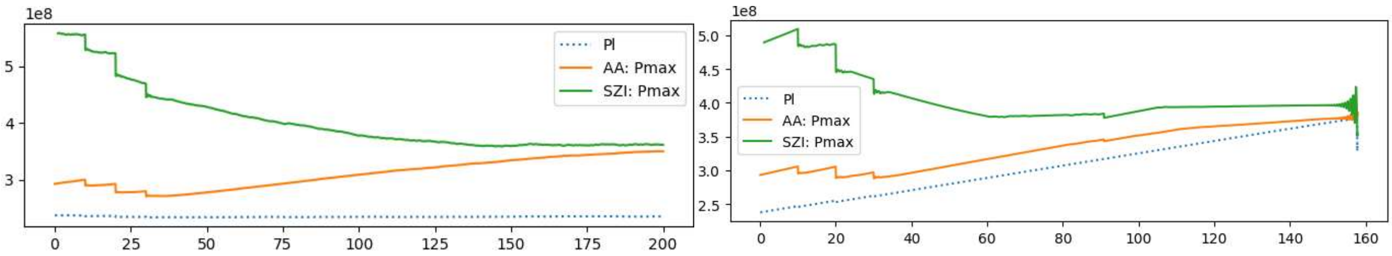

Figure 65 Voltage stability application results E1(left) and E2(right), each with approximated maximum loadability where the blue curve is the actual load from the time domain simulations.

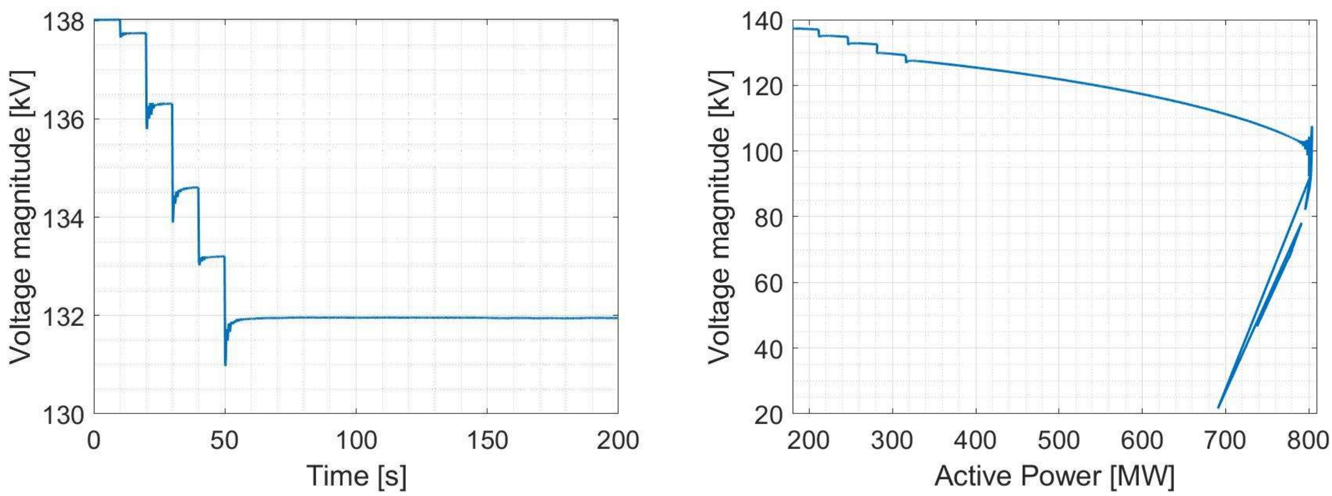

Figure 66 Time domain results for Case E3 (left) presenting the bus voltage at bus A, and Case E4 (right) with the maximum loadability in form of the PV-curve

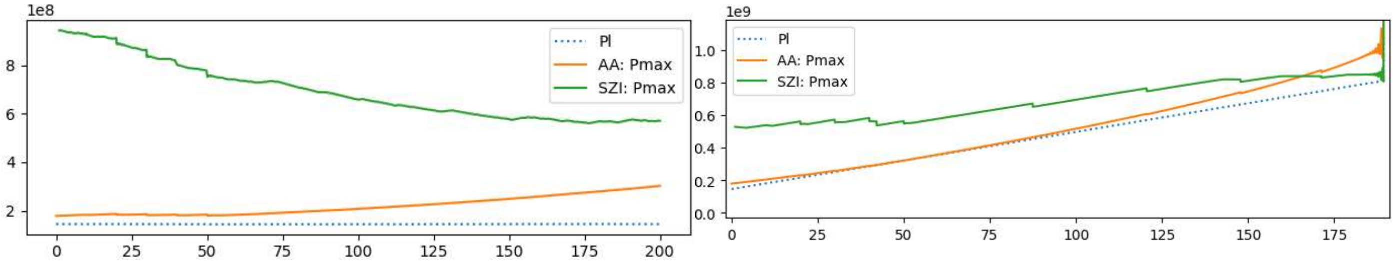

Figure 67 Voltage stability application results for Case E3(left) and E4(right), each with approximated maximum loadability where the blue curve is the actual load from the time domain simulations.

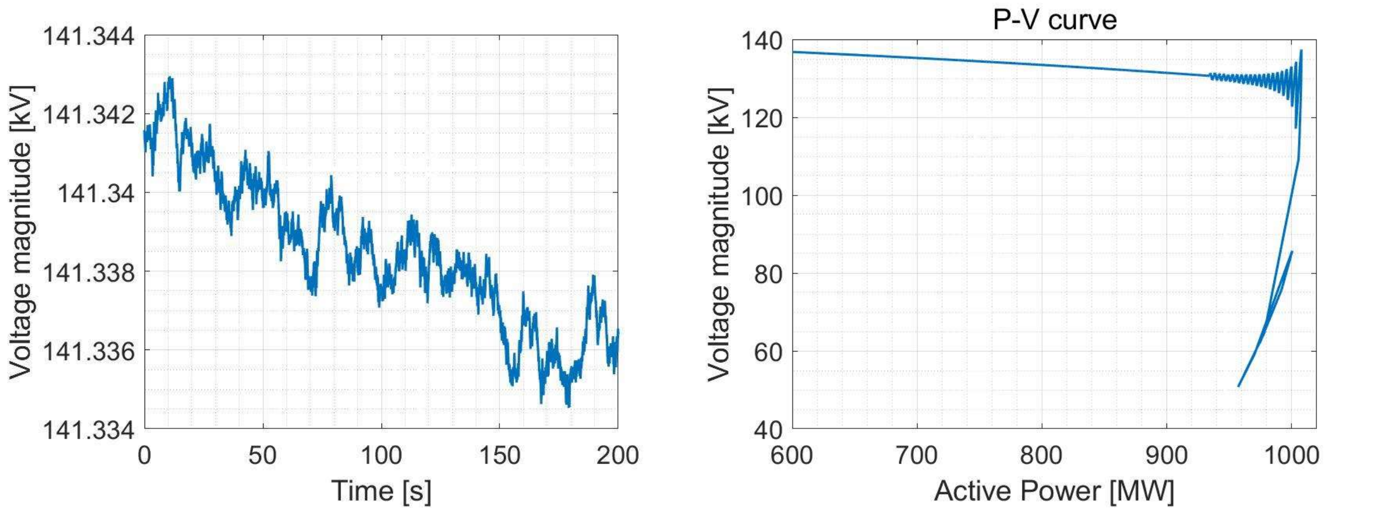

Figure 68 Time domain results for Case E5 (left) presenting the bus voltage at bus A, and Case E6 (right) with the maximum loadability in form of the PV-curve

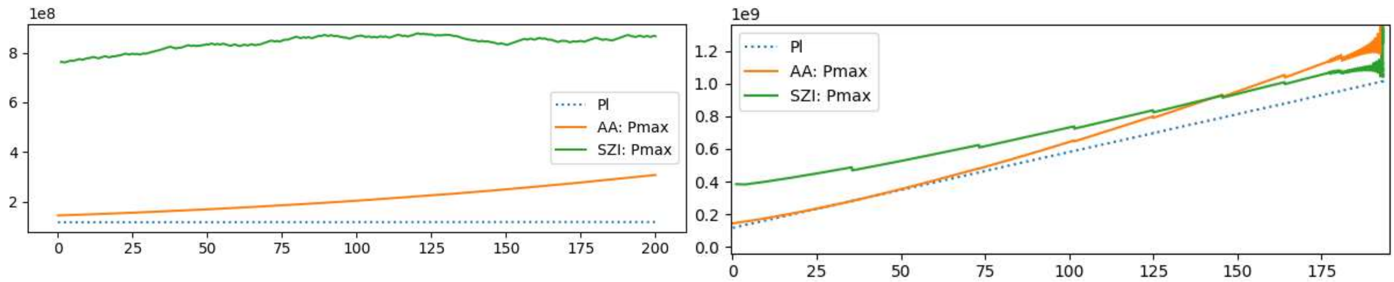

Figure 69 Voltage stability application results for Case E5 (left) and E6 (right), each with approximated maximum loadability where the blue curve is the actual load from the time domain simulations.

Case B3 has been further used to study the sensitivity of the application results, considering parameterisation and erroneous PMU Data.

Addressing the methods of parameterisation sensitivity, changes are made to the input parameter reflecting the X/R ratio of the Thevenin equivalent of the grid. The X/R ratio was originally ≈ 10 and was decreased to ≈ 2. Results are presented in Figure 70, illustrating how the estimated maximum loadability level is changed for the SZI indicator. Thus, highlighting the importance of the X/R parameter to the application results.

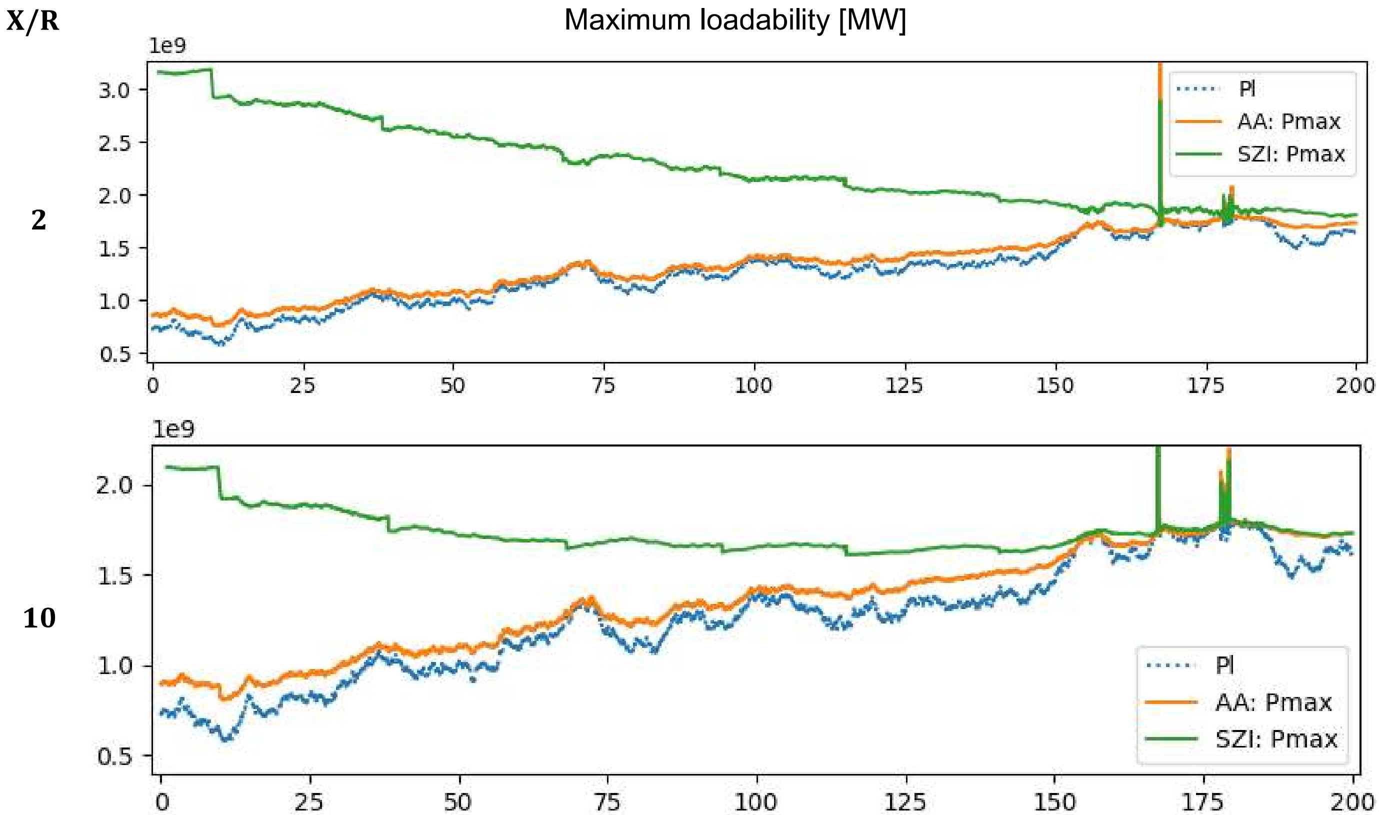

Figure 70 Voltage stability application results for Case B3, varying X/R ratio of the grid Thevenin equivalent, with the approximated maximum loadability where the blue curve is the actual load from the time domain simulations.

Studies of erroneous PMU data include two scenarios: missing data and faulty data, as presented in Figure 71 and Figure 72. In the former case, the output of the application becomes NAN or ZERO for the periods with missing data and continues to provide results when the PMU data stream is recovered. In the latter case, the PMU voltage signal is providing faulty data in the form of an oscillation of approximately 50kV. This fault is transmitted through application and is directly seen in the results.

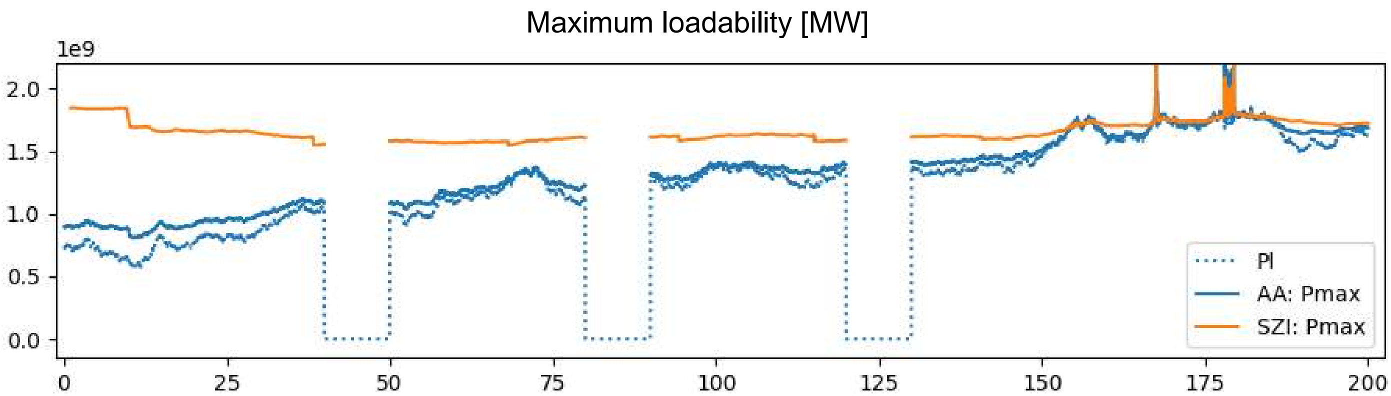

Figure 71 Voltage stability application results for Case B3, with missing PMU data.

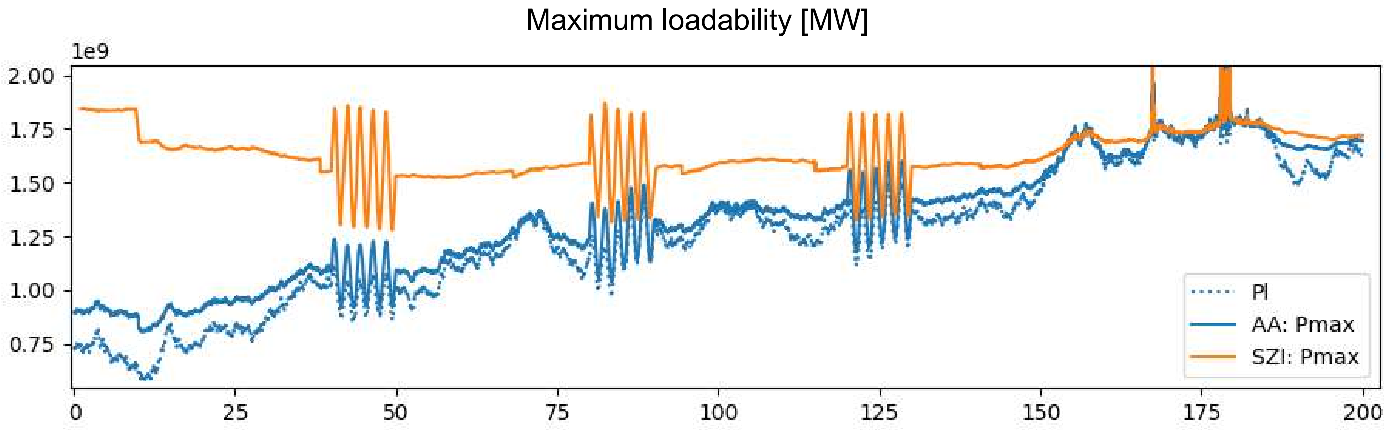

Figure 72 Voltage stability application results for Case B3, with faulty PMU data.

In conclusion:

- Estimation of loadability could be a valuable indicator of how far the system is from voltage instability, however, the tests performed cannot verify a reliable estimation ahead of time. One source of error in the estimation could be how the application assumes the Thevenin equivalent of the system, which could explain why it seems to work fine for some buses. The user could change this assumption in the application code.
- In the tested cases, the voltage stability indicator SZI performs satisfactorily to identify the actual instant of instability.

It should be noted that the developed application is functioning only when there is a change in time of loads or voltage. Furthermore, these applications produce reliable indicators only when the load demand is increasing and when margins to maximum loading are not too large. Practical implementations must therefore disregard input data in very stable operating conditions when load changes are small. This may not be a big drawback since the operators (or automatic control systems) in such situations do not need the information, The voltage instability indicator will normally be increasingly accurate the closer the system is to maximum loadability. The main drawback being that none of these indicators provide any predictions apart from the estimating margins to voltage instability given that the system state remains basically unchanged. Therefore, it is important to emphasise that online voltage stability indicators should be used in combination with model-based voltage stability assessment tools.

4.3 Natural oscillation monitoring and detection

The focus for the natural oscillation monitoring and detection is on modal or natural electromechanical oscillations, which are intrinsic to power systems. Natural oscillations persist within power systems, and if undamped, they can lead to severe system instability or collapse. In this project, previously developed oscillation identification methods have been employed to monitor and identify natural oscillations in real-time. These methods will capture key characteristics such as frequency, damping, and mode shape.

4.3.1 Introduction

Natural oscillations are constantly present in power systems and in the most severe situations undamped oscillations may lead to the collapse of the entire system. In the Nordic power system natural inter-area oscillations limit the power transfer capacity in several corridors, for example between Finland and Sweden. In this project, previously developed oscillation identification methods have been utilised to identify natural oscillations in real-time. For a WAMS application, the identification methods shall identify the characteristics of the oscillations (such as damping, frequency, amplitude, and mode shape). If the oscillations pose a threat to the system (for instance, if the damping is too low) a warning should be raised to the operator.

An overview of the data flow for the oscillation module is illustrated below.

- **Preprocessing**: Select relevant data from a file or data stream.
- **Method**: Apply a data analysis technique for oscillation detection, such as Stochastic Subspace Identification (SSI) or spectral analysis.
- **Analysis**: Interpret the results, focusing on modal analysis and insights derived from the processed data.

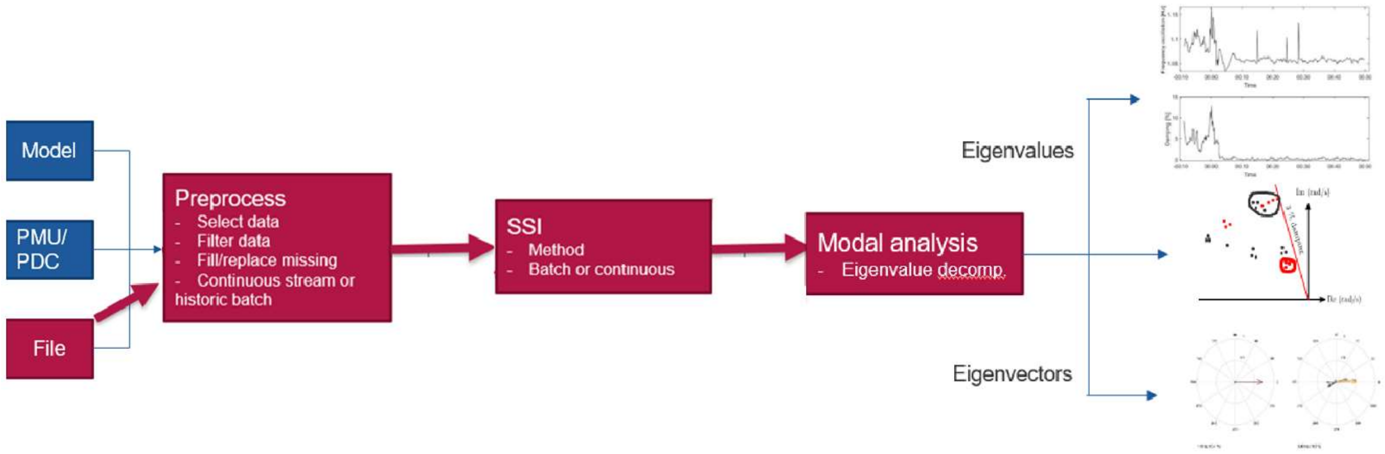

Figure 73: Overview of the data flow for the oscillation identification method.

4.3.2 Oscillation application requirements for an operator

Three different use cases related to inter-area oscillation were identified as most relevant for operators:

- Detection and mitigation.
- Root cause analysis.
- Contingency/look-ahead analysis.

These three use cases are further described below. In the NEWEPS project, the focus has been on detection and mitigation.

Detection and mitigation

Uncontrolled oscillations can result in unnecessary wear and tear of equipment. There is a risk that automatic relays out in the grid fire due to oscillations, disconnection of equipment, and the possibility of islanding/network split.

Disturbance, even small could start the oscillation, damping of oscillation decreases if impedance increases, e.g. line disconnection, lower inertia could also lead to this. Both reduce stability margin.

The detection and mitigation method uses phasor measurements to monitor oscillations in various frequency bands (0.1 – 4 Hz) at multiple measuring locations, alerting the operator if amplitude and damping factor exceeded predefined thresholds.

The detection and mitigation method is intended to provide the operator with decision support for effective mitigation, such as generator re-scheduling within < 15 minutes after detection of the oscillation.

Flow of events:

1. Oscillations, exceeding pre-defined thresholds, are continuously logged for voltage frequency, current, power, or voltage amplitude in different frequency bands (0.1 – 4 Hz).
2. Localisation of units or grid areas mostly involved in oscillations (observability analysis).
3. The user information system provides geographical overview, shows where oscillations are observed and indicates frequency, amplitude and damping (possibly) of the critical modes.

4. The information serves as the foundation for proposed operator actions or automatic responses to mitigate the problem.

Outcome: Handling and stabilizing of critical operating conditions.

Root cause analysis

Disturbances in the grid can have either local or global effects. Changes in average frequency generally do not require a geographically specific response. However, disturbances that impact voltage stability or interarea mode stability tend to be more localised. In such cases, identifying the source of the disturbance is essential for determining an effective and appropriate response.

Examples of disturbances include the disconnection of a transmission line, generating unit, or load centre; loads or generators operating in a way that creates unnecessary disruptions; or poorly tuned controllers, including nonlinear controllers that switch between set points unpredictably.

The inputs used by a root cause analysis method are:

1. Phasor measurements to derive type of oscillation (forced or natural) and type and location of the cause.
2. Baseline of pre-analysed historical oscillation events.

The root cause analysis method is intended to provide the grid supervisor with information to take mitigative actions (e.g. stop faulty loads/generators causing forced oscillations or change operating point for natural underdamped oscillations) within 15 minutes after detection of the oscillation.

Flow of events:

1. A major disturbance occurs.
2. The user is presented an alert message presenting prioritised disturbances that jeopardise power system stability.
3. The user is further presented automatically identified likely root causes and suggested course of actions. Actions can either be in the form of suggestions to the operator or as automatic control function. (e.g. Reduce output power from station, disconnection of components, increased the voltage in STATCOM).

Outcome: Rotor angle and voltage stability issues are detected and mitigated, avoiding islanding and blackouts.

Contingency/look-ahead analysis

During certain situations (certain topology, flow etc.) there might be a risk of oscillations following a N-1-fault. Today, we have no way of monitoring this in the control centre and are therefore unaware of potential risks. The ideal would be a real-time (or close to real-time) contingency analysis that alerts the operator of potential risks. The system would simulate N-1 faults on a current grid model and measure oscillations.

Possible conditions for initiating the contingency/look-ahead analysis are:

1. Periodically (every 3 minutes), for example on state estimation availability.
2. Automatically whenever current stability margins drop below predefined thresholds.
3. On-demand, whenever an exceptional topology and operating point is required.

The input data needed by a contingency/look-ahead analysis are:

1. Phasor measurements to derive type of oscillation (forced or natural) and the location of the cause.
2. Baseline of pre-analysed historical oscillation events.

3. Dynamic models initialised from base-case state estimations. Small signal stability involves the whole system; therefore, the use of complete (dynamic) models of systems is necessary.

Contingency/look-ahead analysis methods are intended to provide the grid supervisor with information to assimilate the situation and implement preventive measures. The method can be used by power system planners for fault analysis and operation planning.

Flow of events:

1. The user is presented with a list of expected oscillations and suggestions for measures to enhance dynamic security.
2. For example, information on which areas the generators contribute to damping, and in which way they induce oscillation and where we should address the problem in order to:
    a. Identifying poorly tuned controllers and if possible, fixing/removing these.
    b. Identifying operating conditions with a high risk of instability.
        i. Baseline oscillation scenario can be used to suggest a course of action when oscillations are detected by grid supervisors.
        ii. Can be used for planned maintenance operations.
3. This is used, e.g., to identify suitable PSS or POD control locations, in order to improve stability of interarea oscillations.

Outcome: Improved stability margins allow for more flexible operation of the grid. Knowledge of the root causes allows for tuning/fixing controllers to improve stability margins and/or knowledge of which operating conditions to avoid.

4.3.3 Stability theory and methods

Power system linearisation

Power system dynamics are inherently nonlinear and are governed by differential-algebraic equations, where the state, algebraic variables, and control inputs interact in complex ways. To analyse the small signal stability of electromechanical oscillations, these equations can be linearised around an operating point.

Linearisation simplifies the dynamics by considering small deviations, yielding a linear time-invariant state-space representation. This representation allows for analysis of system stability through the computation of eigenvalues, eigenvectors, and other critical parameters. As such, power system linearisation provides a practical and computationally efficient foundation for assessing and mitigating natural oscillations in power systems.

The dynamics of a power system can be described by a set of differential algebraic equations:

$$\dot{x} = f(x, \gamma, u)$$
$$0 = g(x, \gamma, u)$$

where vectors x and γ contain system state and algebraic variables, respectively. The vector u contains control inputs. For the purpose of analysing the small signal stability of electromechanical modes, a linearised model suffices. The linearised model considers small deviations [Δx,Δγ,Δu] around an operating point [x∗,γ∗,u∗].

$$\Delta\dot{x} = \left(\frac{\partial f}{\partial x} - \frac{\partial f}{\partial \gamma}\left(\frac{\partial g}{\partial \gamma}\right)^{-1}\frac{\partial g}{\partial x}\right)\Delta x + \left(\frac{\partial f}{\partial u} - \frac{\partial f}{\partial \gamma}\left(\frac{\partial g}{\partial \gamma}\right)^{-1}\frac{\partial g}{\partial u}\right)\Delta u$$

Deviations are assumed sufficiently small so that (if $\partial g/\partial \gamma$ is invertible) the linearised model accurately describes system dynamics. Since the linear model always considers deviations around the operating point, the Δ notation can be dropped. The linearised model gives a linear time-invariant state-space representation:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

where A and B are system state and input matrices given by the partial derivatives, and y is the output with output matrix C and direct feed-through matrix D.

Oscillation identification method

There are several oscillation identification methods using measurement data, with different strengths and weaknesses. The SSI (stochastic subspace identification) method is selected in this project due to its ease of implementation, numerical stability, and ability to work with ambient (non-disturbance) data.

In the SSI technique, a parametric model is fitted to times series data[55], [56], [57]. In general, we are looking for a set of parameters that will minimise the deviation between estimates and the measured system response. This approach still provides a continuous estimate in scenarios where the system response lacks a strong transient signal, such as when the oscillations are weakly excited or embedded in ambient noise.

The SSI algorithm works in three steps:

1. Form a covariance matrix from the measurements Y.
2. Calculate the observability matrix by singular value decomposition (SVD).
3. Extract matrices (A and C) from the observability matrix

Linear and time-invariant time domain modal identification techniques can be formulated in a generalised form by the state space formulation:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

where the A-matrix contains the physical information and the C-matrix the observability of the system. If input signals are known, then input matrix B and direct feedthrough matrix D can be estimated as well.

Prony's method[58] has been used to validate the results from the SSI algorithm during a ring-down scenario. It is a method of fitting a linear combination of exponential terms:

$$y(t) = \sum_{n=1}^{N} A_n e^{\sigma_n t} \cos\left(2\pi f_n t + \theta_n\right), \quad n = 1, 2, 3, \ldots, N.$$

where $y(t)$ is a function of time, t, and A_n σ_n, f_n and θ_n are the amplitude, attenuation, frequency and phase shift of component n of N.

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[55] Van Overschee, P., & De Moor, B. (1996). Subspace identification for linear systems: Theory—Implementation—Applications. K2luwer academic publishers.

[56] Sarmadi, S., & Venkatasubramanian, V. (2013). Electromechanical Mode Estimation Using Recursive Adaptive Stochastic Subspace Identification. IEEE Transactions on power systems.

[57] Jingmin, N., Chen, S., & Feng, L. (2011). Estimating the Electromechanical Oscillation Characteristics of Power System Based on Measured Ambient Data Utilizing Stochastic Subspace Method. 2011 IEEE Power and Energy Society General Meeting.

[58] Føyen, S., Kvammen, M., & Fosso, O. (2018). Prony's method as a tool for power system identification in Smart Grids 24th IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion 2018.

Modal analysis

Modes of the linearised system model are analysed by computing eigenvalues (modes) and eigenvectors. These provide information regarding frequency and damping of oscillatory modes, as well as information on the observability and controllability of the modes. In particular, analysis of these quantities allows uncovering the participation in natural oscillatory modes (especially low damped inter-area modes) of the various grid components (especially generators). It is important to be able to track the most important oscillations over time. Therefore, it is insufficient to only estimate the frequency and damping of an oscillation, since this lacks information on the involved generators. An alternative view of tracking the oscillations across time is to consider the observability of modes over time and cluster these observability levels over time. The proposition is that the observability modes will be more consistent with the topology of the network than only the eigenvalues, since they vary based on the active controls and on-line generators.

4.3.4 SSI model parameterisation and preprocessing

The input data to the method is considered to be standardised frequency datasets from multiple PMUs. If the input data is provided with 50 Hz resolution, it is down-sampled to 10 Hz, which is sufficient for looking at natural oscillations (local and interarea modes typically < 2 Hz). The SSI method executes an identification over a window of 1 minute and performs a system identification. The data is filtered to remove the slow average trend to enhance performance.

The SSI method is parametrised through several variables that control the system's model estimation and the handling of data. These parameters influence the time window for covariance matrix calculation, mode extraction, and the filtering of system dynamics.

Time Window Parameters:

> **Recursive Window Length (`I_seconds`)**: Defines the length of the time window (in seconds) used for computing the covariance matrix. This window determines how much historical data is considered for each covariance update. In this implementation, the recursive window length is set to 8 seconds.
>
> **Refresh Rate (`R_seconds`)**: Specifies the time interval (in seconds) at which the model refreshes and updates its estimates using new data. It is set to 0.5 seconds, meaning the model processes data in small time steps to capture rapid changes in the system.
>
> **Covariance Matrix Update:**
>
> The covariance matrix is updated iteratively over time using a **forgetting factor** (`mu`). This factor allows the model to prioritise recent measurements while gradually diminishing the influence of older data. The forgetting factor is typically set close to 1. In this project it is set to 0.98.

State-Space Model and Modal Estimation:

> **Number of States (`n_states`)**: The number of system states retained in the modal analysis is set to 20. This parameter controls the complexity of the model, and the number of modes estimated.
>
> **Sorting and Filtering Criteria**: Modes can optionally be filtered based on frequency (`f_cutoff_high` and `f_cutoff_low`) and damping ratio (`d_max`) to discard irrelevant or non-physical modes. The remaining modes can be sorted by frequency or damping, as specified in the `opt['sort']` parameter, set to frequency. In this project, the filter parameters are unused (set to None), and the max damping ratio is set to be 0.3.

Overall, the parametrisation of the SSI method involves selecting the time window length, refresh rate, and mode filtering criteria to balance the model's responsiveness to data and its ability to extract meaningful system dynamics. The recursive window size and update intervals directly influence the temporal resolution of the model, enabling the SSI method to effectively track dynamic changes over time.

4.3.5 Theoretical validation and test results

To theoretically validate the system identification algorithms, a linearised version of the Nordic 5-machine test system (N5)[59] is utilised. The system modes are calculated from the A-matrix, which consists of four natural frequencies: 0.41 Hz, 0.61 Hz, 1.01 Hz, and 2.3 Hz, all with approximately 0-1% damping. The frequency and damping of modes are summarised in Table 6.

Table 6: Theoretically calculated frequency and damping of modes in the N5 test system

f (Hz)	0.41	0.61	1.01	2.3
ζ (%)	0.8	0.6	0.3	0.2

The system is subjected to a 500 MW disturbance (load step), which provides a basis for the identification of the system's natural modes using different algorithms.

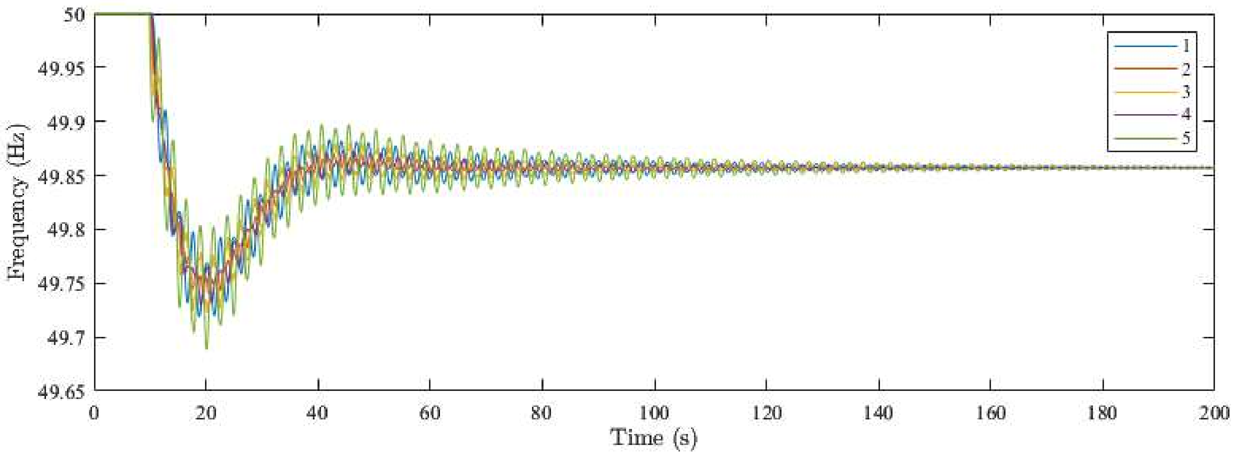

Figure 74: Frequency signals for each bus in the N5 test system used to derive the system modes.

Theoretical validation of the Prony method

The Prony method successfully identifies all four system modes, however the estimation of damping varies between 0-3%. It should be noted that five estimations were performed, one for each bus frequency input.

Table 7: Frequency and damping of modes in the N5-test system, derived by the Prony method using frequency measurements of all 5 buses.

f (Hz)	0.41	0.61	1.01	2.3
ζ (%)	2.1	2.4	1.7	2.6

In Figure 75, mode shapes (compass plots) are used to visualise the results. The compass plots illustrate the signals associated with the power oscillations in the system. Each arrow represents the phase and amplitude of the oscillation at a particular point (i.e., at one of the 5 buses) in the studied system. The direction of the arrow shows the phase, and its length indicates the amplitude of the oscillation mode at that point. For example, if the

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[59] J. Björk, K. H. Johansson, and F. Dörfler, "Dynamic Virtual Power Plant Design for Fast Frequency Reserves: Coordinating Hydro and Wind", IEEE Transactions on Control of Network Systems, vol. 10, no. 3, September 2023, pp. 1266-1278
Model details available: https://github.com/joakimbjork/Nordic5

arrows are 180 degrees apart, this indicates that the signals are oscillating in opposition to each other, meaning they are out of phase.

The 2.3 Hz mode shows only one arrow, which indicates that this mode is primarily observable at bus 3. This means that the oscillation at bus 3 is dominant, and there is little to no oscillation at the other buses in the system, which is characteristic of a local mode or a mode that is not coupled with the rest of the system.

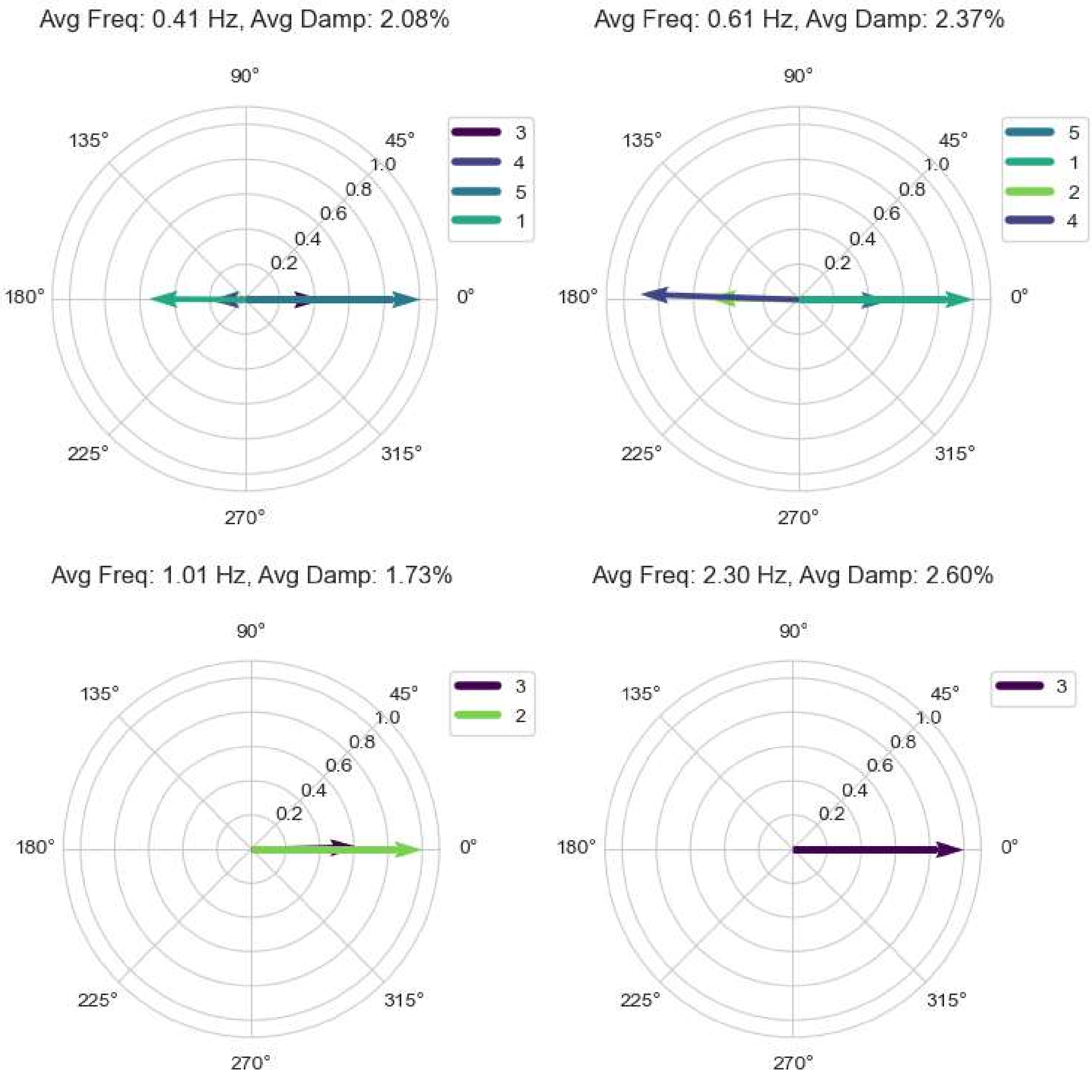


Figure 75: Compass plots for all four system modes, each showing the Prony method´s estimates of the damping based on the five measurements.

Theoretical validation of the SSI method

The results from the SSI method, presented in Table 8, similarly show that all system modes are identified, with very well identified damping estimates.

Table 8: Frequency and damping of modes in the N5-test system, derived by the SSI method using frequency measurements of all 5 buses.

f (Hz)	0.41	0.61	1.01	2.3
ζ (%)	0.8	0.6	0.3	0.2

In Figure 76, mode shapes (compass plots) are used to visualise the results. One strength of the SSI compared to Prony's method is that the estimates are calculated using all inputs simultaneously and not separately. The SSI results confirm the findings from the Prony analysis, where the 2.3 Hz mode is detected only by measurements at bus 3.

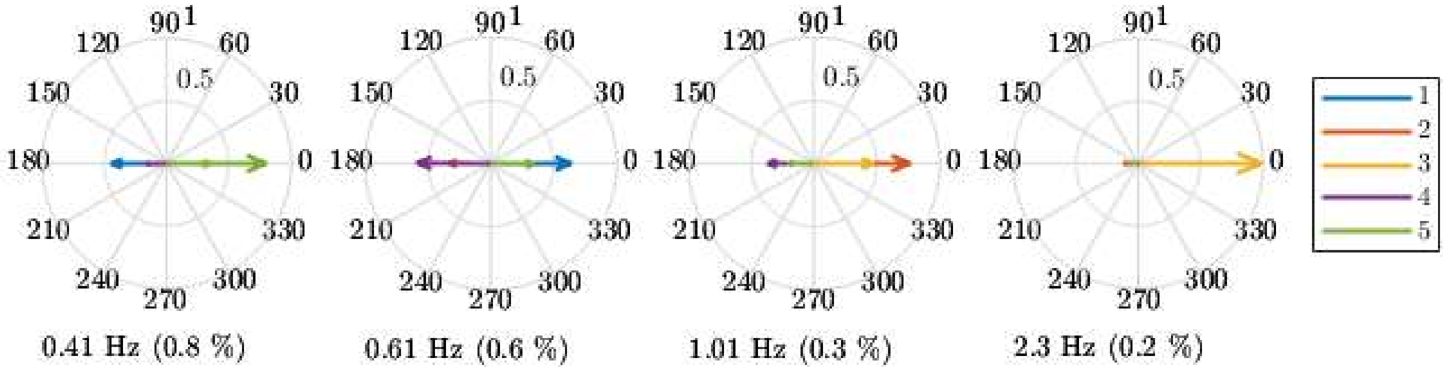


Figure 76: Compass plots for all four system modes, each showing the SSI method´s estimates of the damping based on the five measurements.

Application test using historical PMU data[60]

The test of the SSI algorithm is exemplified through a real data scenario involving 10 Hz resolution measurements from 8 PMUs in the Nordic grid. The left side of Figure 77 provides a visual representation of the frequency deviation signals for the studied 180 s time interval. Here, a pre-filtering process has been applied to eliminate frequencies below 0.125 Hz. The resulting mode estimates generated by the algorithm are presented on the right side of Figure 77. Estimates are included for each time window within 180 seconds, where a colour scale is used to illustrate how estimates move in time. Lines representing 3, 5, and 7% damping ratio are also included.

From the mode estimates presented in Figure 77, it is evident that there is an undamped oscillation of approximately 1.0 Hz. Different methods for oscillation tracking have been explored in the project. In Figure 78, we simply opt for a naive method of following the lowest damped estimate over time. As these results illustrate, the solution does not provide a way to follow a single mode since the lowest damped estimate varies in time.

[60] Hillberg, E., et al., *Standards-based interoperable testbed for development and assessment of stability monitoring applications in the Nordic interconnected grid*, CIGRE, Paris, 2024

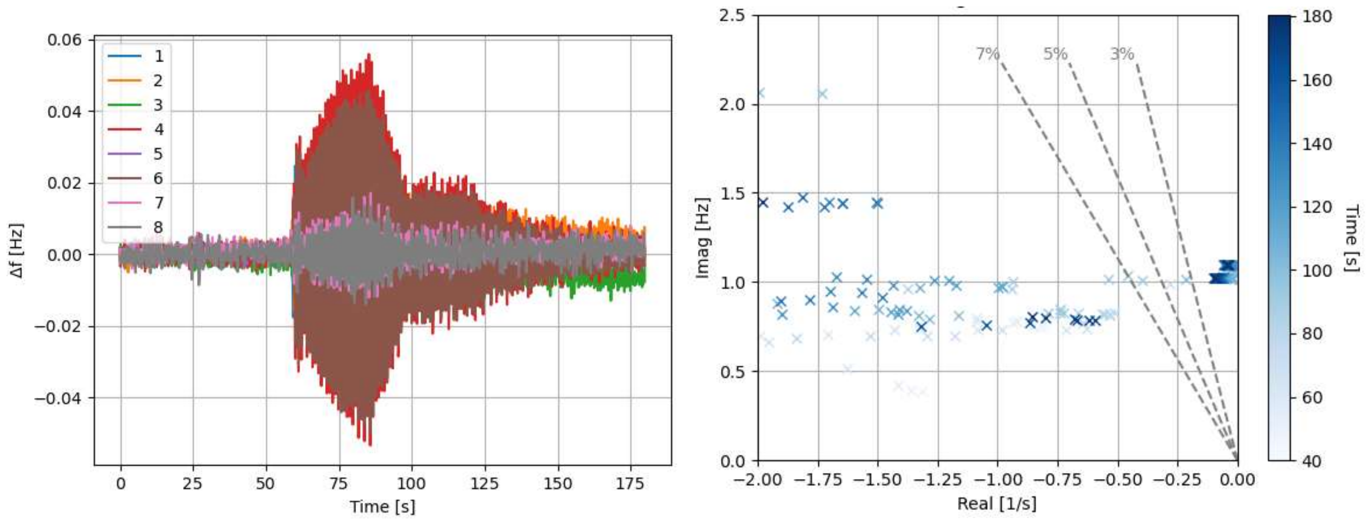


Figure 77: Left: Frequency signals from 8 PMUs in the Nordic grid. Right: SSI mode estimates from the analysed 180 seconds.

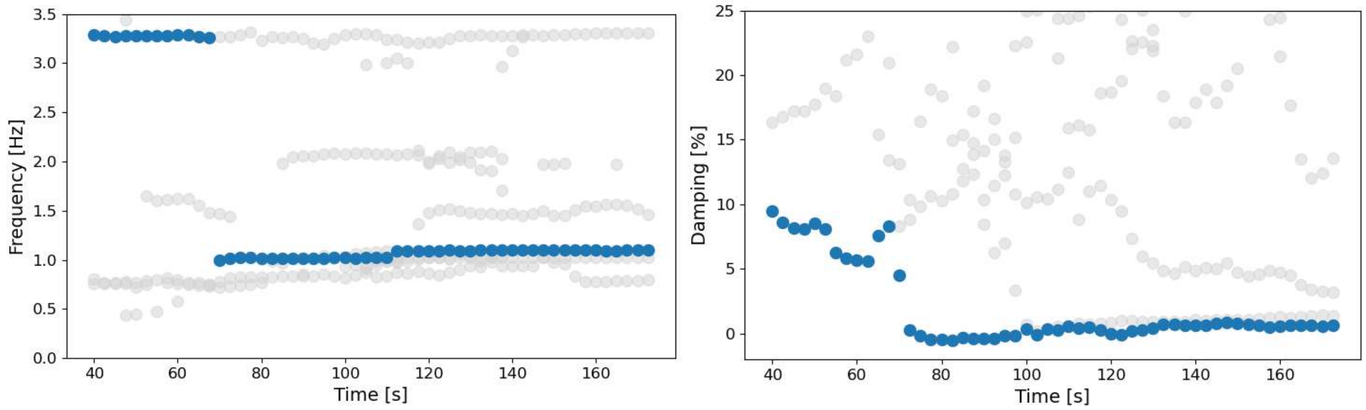


Figure 78: Mode estimates followed in time. Lowest damped estimate marked in blue. Left: Oscillatory frequency. Right: Damping ratio.

Improved ways to follow a critical mode include clustering of mode estimates, which is illustrated in Figure 78 and Figure 80. The mode shapes connected to the mode estimates describe the observability amplitude and relative phase of the mode from each measurement used in the estimate. In this way, the structure of the mode shape provides added information on the identity of a mode supporting the tracking of an estimate in time. There are several solutions to cluster estimates, such as the k-Means clustering algorithm described in detail in [61]. In this example, a recursive mode shape tracking solution is implemented which evaluates the fit of the cluster estimates online.

[61] H. Haugdal and K. Uhlen, *Mode Shape Estimation using Complex Principal Component Analysis and k-Means Clustering*, International Conference on Smart Grid Synchronised Measurements and Analytics (SGSMA), 2019

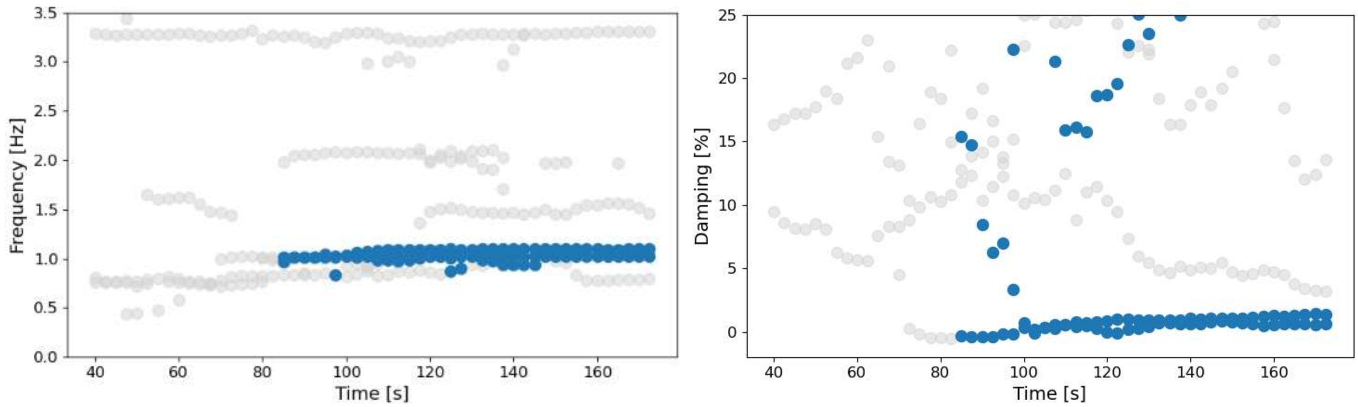


Figure 79: Mode estimates followed in time. Identified clustered estimate highlighted in blue. Left: Oscillatory frequency. Right: Damping ratio.

The (compass plot) mode shape, shown in Figure 80, represents the target signature for the blue cluster in Figure 79 with an average frequency of 1.03 Hz and damping ratio of 6.0%. The light grey arrows in Figure 80 represent the mode shape from each time frame of the blue estimates in Figure 79.

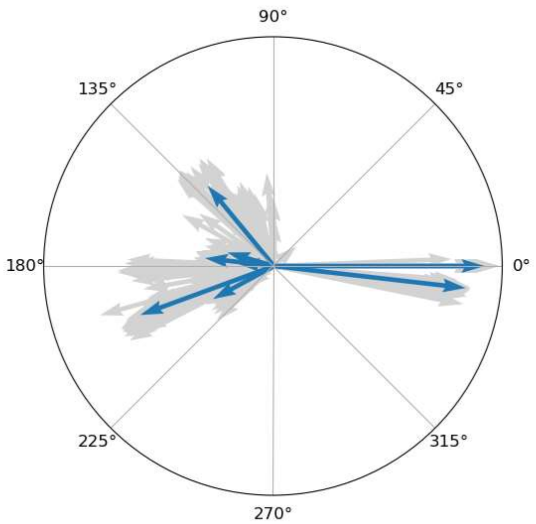


Figure 80: Mode shape of the identified clustered estimate highlighted in blue in Figure 79.

4.3.6 Application validation

As for testing the Voltage stability application, tests of the natural oscillation application were performed by using PMU data files created based on simulations in PSS/E.

Also, for this application a large number of test cases have been studied, and in this report only a few of these are presented. The cases presented are listed in the table below and are further described in text. Simulations are preformed using the Nordic44 test system[62] (N44) and a Swedish planning model[63] provided by Svenska kraftnät (Svk).

[62] An aggregated model of the Nordic power system containing 44 buses.

[63] Planning model containing over 4700 buses.

Table 9: List of simulation test cases presented in this report.

Case	Model	Comment
A1	N44	Step in active power generation
A2	N44	Same active power step with white noise applied on a limited set (10%) of the load.
A3	N44	Same active power step with white noise applied on about half of the loads
A4	N44	Same active power step with random walk noise applied on a limited set (10%) of the load
A5	N44	Same active power step with random walk noise applied on about half of the loads
C1	Svk	Short-circuit applied in 10ms
C2	Svk	Short-circuit applied in 10ms with random walk noise applied on a limited amount (10%) of the load
D1	Svk	No disturbance, random walk noise applied on a limited amount (10%) of the load, analysis based on 16 channels
D2	Svk	Line trip, no noise, analysis based on 182 channels
D3	Svk	Line trip, random walk noise applied on a limited amount (10%) of the load, analysis based on 182 channels

Cases A (using N44 model), C and D (both using Svenska kraftnät model) are used for the validation of the oscillation monitoring application. The purpose of these test cases is to evaluate how well the frequency and damping of low damped natural oscillations can be estimated.

- Cases A1 to A5: simulated small disturbance in the form of a step in active power generation[64] of one generator in the N44 model, applying different type of noise to the load. All Power System Stabilizers (PSS) are initially deactivated, and at t = 100 s one PSS[65] was activated.
  - Goal: evaluate oscillation monitoring application against the eigenvalues provided through linearisation[66].
- Cases C1 and C2: simulated small disturbance in the form of a short-circuit on the bus[67] of one generator in the Svenska kraftnät model, with or without noise applied to the load.
  - Goal: evaluate oscillation monitoring application estimation in a scenario with low excitation of oscillatory frequencies against time domain results[68]. A comparison is also made with results from linearisation[69].
- Case D1: no disturbance event, random walk noise applied to the load in the Svenska kraftnät model.
  - Goal: evaluate how the oscillation monitoring application estimation is on ambient data only.
- Cases D2 and D3: simulated large disturbance in the form of a line trip[70] in the Svenska kraftnät model, with or without noise applied to the load.
  - Goal: evaluate how the oscillation monitoring application estimation is impacted by noise as well as by the level of PMU coverage.

[64] Active power step increase of about 4% applied at one of the generators at t = 10 s. The generator to which the step increase was applied corresponds to a hydro plant, with a HYGOV turbine governor with the governor time constant 5.

[65] PSS of the generator connected to the same bus as the generator with the active power step.

[66] Linearization performed using the simulation tool Power Factory by DIgSILENT 2024 SP1.

[67] Short-circuit applied for 10ms at one of the generators at t = 40 s.

[68] Time domain estimation of oscillation frequency and damping done by using the logarithmic decrement method.

[69] The linearised model is only used as an approximate comparison, due to the limitations of the linearization tool used PSS SINCAL.

[70] At t = 40 s, trip of a located in Sweden with an active power flow of about 420 MW before the trip.

Oscillation monitoring – Application validation results

These tests are made to evaluate the ability to estimate the natural oscillatory modes of the studied system under varying conditions. Validation of results are made in two ways: based on results from linearisation of the study model and based on results from manual estimation of the time domain simulations using a logarithmic decrement method.

The logarithmic decrement method is defined by the below equations. It requires two consecutive points, $\{x_1,y_1\}$ $\{x_{n+1},y_{n+1}\}$, separated by n times T on a sinusoidal signal to calculate the oscillation and damping of the oscillation.

Damping: $\zeta = -\frac{\delta}{\sqrt{(2\pi f)^2+\delta^2}}$; where $\delta = -\frac{f}{n}\ln\left|\frac{y_1}{y_{n+1}}\right|$ and $f = \frac{1}{T} = \frac{n}{x_{n+1}-x_1}$

The ability of mode estimation from measurements depends on the location and amount of available measurement points, and this impact is also evaluated.

The study started using the N44 model, with cases A1-A5, evaluating the estimation results for a small signal disturbance when the system has different levels of noise. In these cases, the generator 2 on bus 5300 is influenced by a step in the active power setpoint at t=10 s, and the PSS at generator 1 on bus 5300 is activated at t=100 s.

In Figure 81, the time domain results for case A1 (no noise) are represented by the active power of the generator which is impacted by a small disturbance and the frequencies in three places in the system (it should be noted that the amplitude of the frequency change is less than 5 mHz).

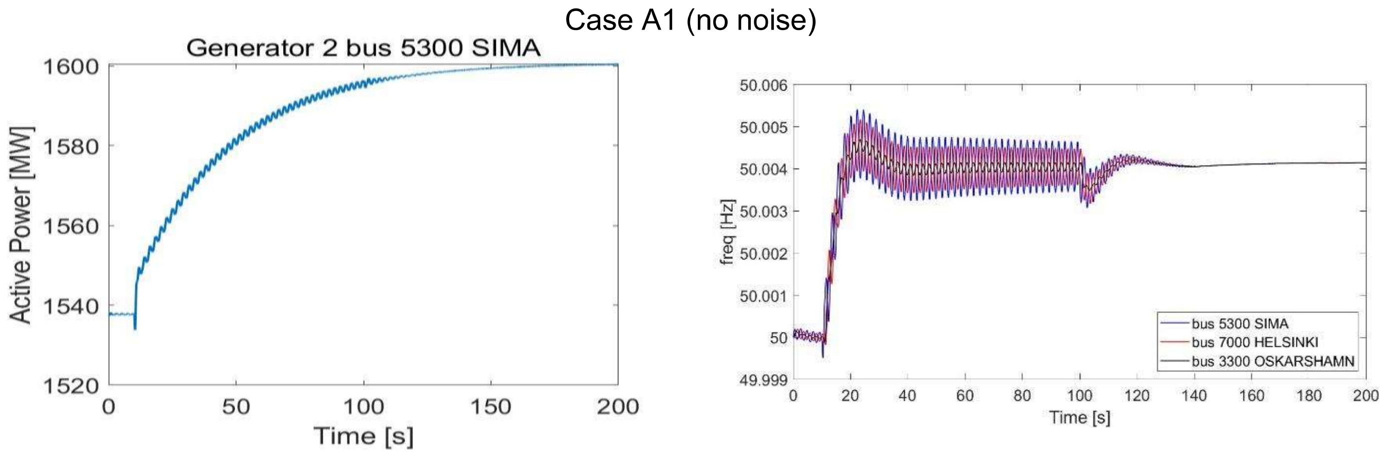


Figure 81 Time domain simulation results for Case A1: active power of generator 2 bus 5300 (left) and frequencies at three buses in the system (right).

In Figure 82, the time domain results for case A2 and A3 are presented, where white noise is added to 10% and 50% of the buses, respectively, in a comparison with case A1. The amplitude of the frequency change is now increased up to above 10 mHz.

In Figure 83, the time domain results for case A4 and A5 are presented, where random walk noise is added to 10% and 50% of the buses, respectively, in a comparison with case A1. The amplitude of the frequency change is now increased up to 80 mHz.

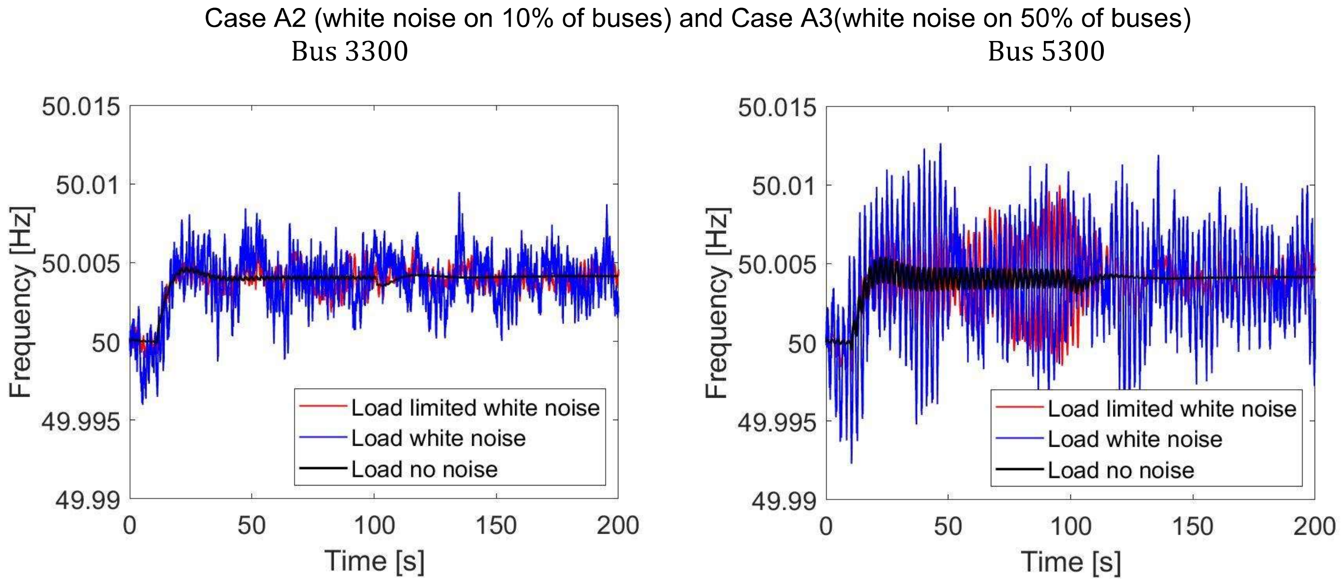


Figure 82 Time domain simulation with frequencies at two buses for Case A1 (no noise / black) Case A2 (white noise on 10% of buses / blue) and Case A3(white noise on 50% of buses / red).

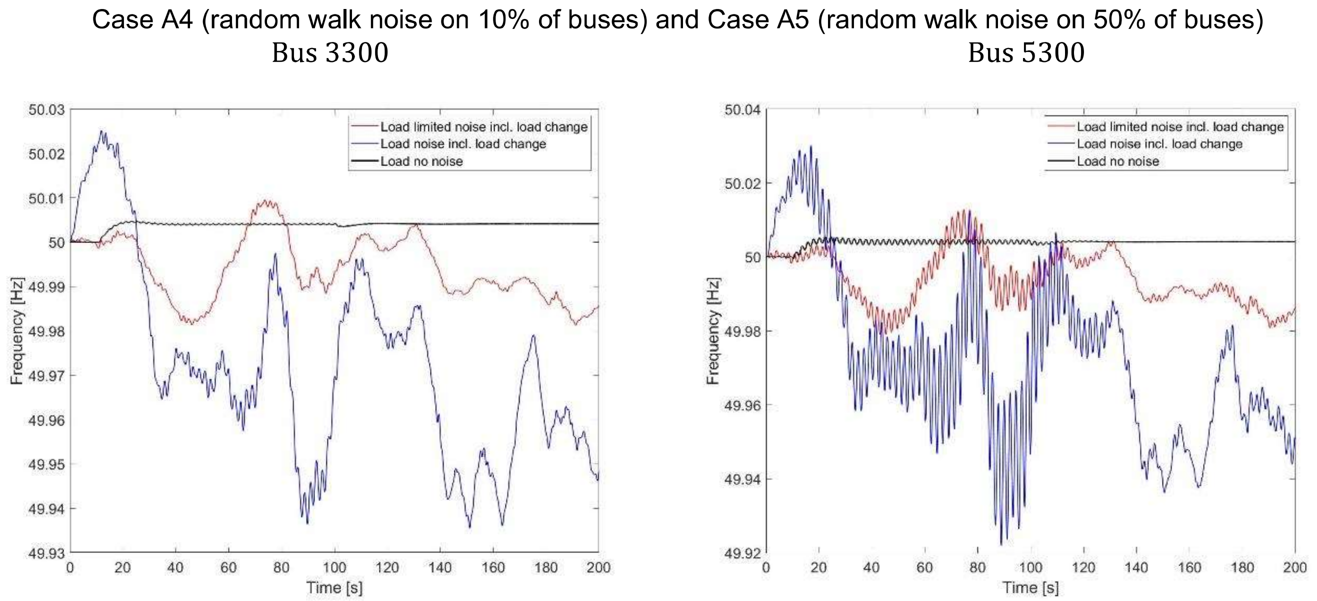


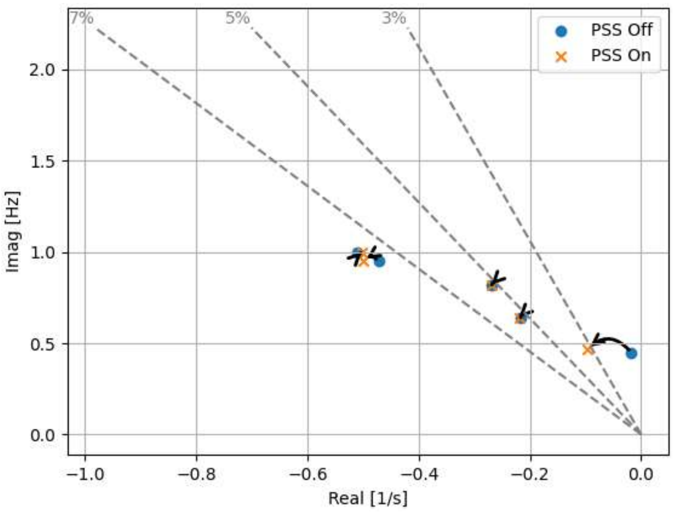
Figure 83 Time domain simulation with frequencies at two buses for Case A1 (no noise / black) Case A4 (random walk noise on 10% of buses / blue) and Case A5(random walk noise on 50% of buses / red).

The noise implemented in Cases A2-A5 has a direct impact in obscuring the observability of the small signal event and the resulting oscillation but can also have the effect of increased oscillation levels due to additional excitation of the low damped modes.

Validation is done against the results of the linearised model, which are presented in Figure 84.

System model linearisation: least damped oscillatory modes

Root-locus plot



List of eigenvalues

Mode	PSS	Frequency (f) [Hz]	Damping (ζ) [%]
1	OFF	0.45	0.64
	ON	0.47	3.27
2	OFF	0.64	5.38
	ON	0.64	5.46
3	OFF	0.82	5.22
	ON	0.82	5.23
4	OFF	0.95	7.90
	ON	0.95	8.36
5	OFF	1.00	8.12
	ON	1.01	8.04

Figure 84 Linearisation of the N44 model. Root locus plot illustrates how modes are shifted if PSS is deactivated (O) and activated (X) on generator 1 bus 5300. Detailed results are included in the table.

The following assessment of the oscillatory modes by the oscillation monitoring application is performed for cases A1 to A5, where one estimation is made for the first part of the studied time period (where all PSS are deactivated) and another estimation for the second half of the time period (where the PSS on generator 1 bus 5300 is activated). Results from these estimations are presented in Table 10 for cases where PSS is deactivated and in Table 11 for cases where PSS is activated. Estimates are compared with the linearisation results and are sometimes missing due to the inability to identify an estimate of the respective mode. Only estimates with damping < 10% are presented.

Table 10: Application estimates for Cases A1 to A5 with PSS deactivated

		Linearisation		Case A1 (no noise)		Case A2 (white noise 10%)		Case A3 (white noise 50%)		Case A4[71] (random walk noise 10%)		Case A5[72] (random walk noise 50%)	
Mode	**PSS**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**
1	OFF	0.45	0.64	0.46	0.2	0.46	0.0	0.46	2.1	0.45	0.0	0.45	0.0
2	OFF	0.64	5.38	0.65	4.9	0.65	4.2			0.64	1.7	0.68	3.8
3	OFF	0.82	5.22	0.83	4.9					0.7	4.1	0.84	3.7
4	OFF	0.95	7.90	0.94	5.6					0.96	5.4		
5	OFF	1.00	8.12							0.98	2.0		

[71] In case A_4, additional low damped modes were identified, with PSS OFF: {0.28Hz, 1.2%} {0.32Hz, 3.4%} {0.41Hz, 0.6%} {0.55Hz, 1.5%}

[72] In case A_5, additional low damped modes were identified, with PSS OFF: {0.19Hz, 5.5%} {0.26Hz, 4.8%} {0.35Hz, 6.2%} {0.41Hz, 2.9%} {0.51Hz, 3.9%} {0.55Hz, 2.4%} {0.78Hz, 2.4%}

Table 11 Application estimates for Cases A1 to A5 with PSS activated

		Linearisation		Case A1 (no noise)		Case A2 (white noise 10%)		Case A3 (white noise 50%)		Case A4[73] (random walk noise 10%)		Case A5[74] (random walk noise 50%)	
Mode	**PSS**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**
1	ON	0.47	3.27	0.45	3.5	0.47	0.7	0.48	2.0	0.47	1.6	0.46	1.4
2	ON	0.64	5.46	0.65	7.3	0.64	3.1	0.65	9.0	0.66	0.3	0.63	3.4
3	ON	0.82	5.23					0.81	3.6	0.8	7.0	0.84	1.4
4	ON	0.95	8.36					0.9	9.0	0.96	6.1	0.91	4.5
5	ON	1.01	8.04			1.05	9.7			1.05	3.1	1.01	5.3

From these results, it is possible to make the following remarks:

- The lowest damped mode is very well estimated in all scenarios, as is further illustrated in Figure 85
- Cases A2 and A3, with white noise, are unable to provide estimates for several of the modes
- Cases A4 and A5 provide estimates for a larger number of modes which are not present in the linearised model (see footnote)

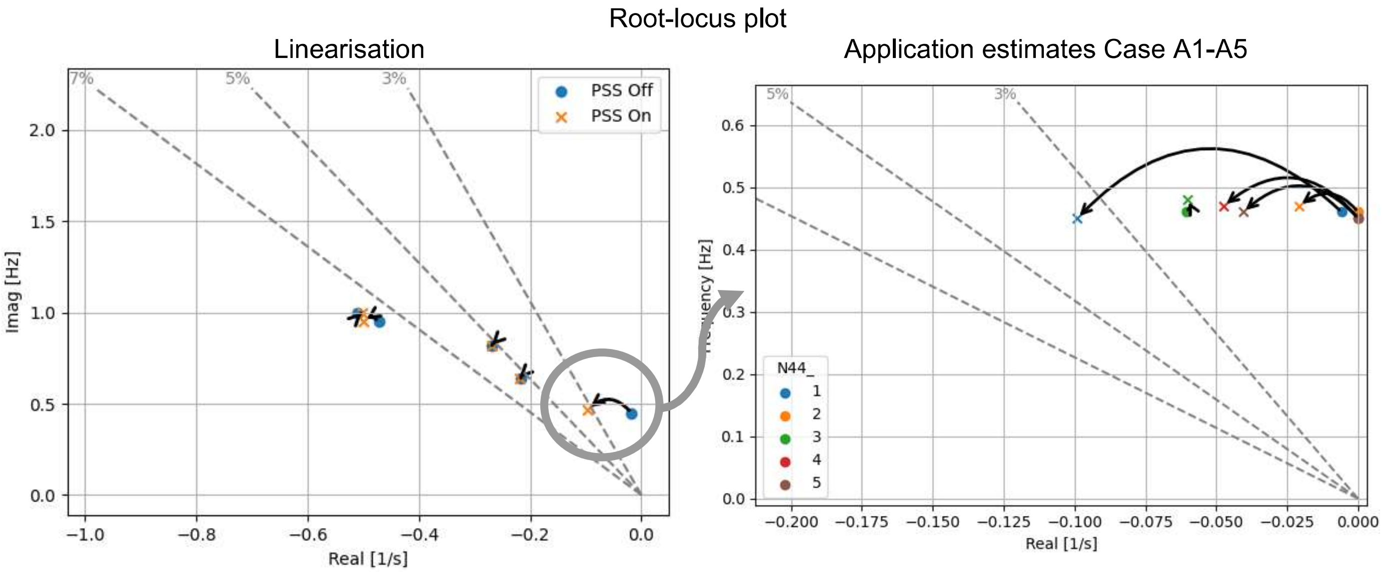


Figure 85 Root locus plot comparing lowest damped mode from linearisation (left) and application estimates (right) where PSS is deactivated (O) and activated (X) on generator 1 bus 5300.

The recursive mode tracking method mentioned in section 4.3.5 was utilised for case A1, with PSS deactivated/activated. The mode shapes were determined for the modes with lowest frequency presented in Figure 85, to validate the possibility to track the mode estimates over time. The mode shapes for the 0.45 and 0.65 Hz modes are presented in Figure 86. As previously presented, in Table 10 and Table 11, the frequency

73 In case A_4, additional low damped modes were identified, with PSS ON: {0.21Hz, 1.2%} {0.36Hz, 4.6%} {0.41Hz, 0.0%} {0.53Hz, 2.2%}

74 In case A_5, additional low damped modes were identified, with PSS ON: {0.19Hz, 1.3%} {0.31Hz, 1.3%} {0.36Hz, 4.6%} {0.41Hz, 7.3%} {0.49Hz, 0.0%} {0.72Hz, 2.6%}

and damping of the modes are changed due to the influence of the PSS. However, the mode shape signature is consistent, pointing at the same observability levels at the measurement location.

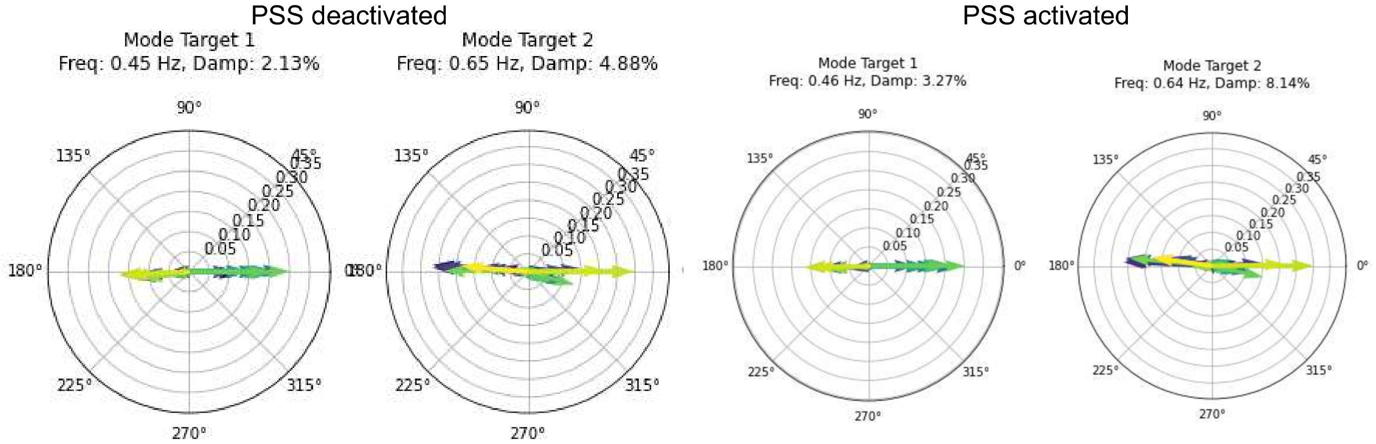
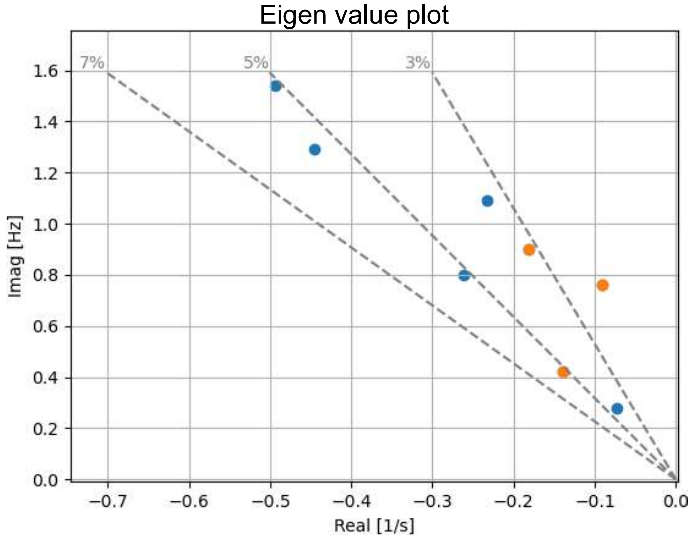


Figure 86: Mode shape plots of the N44 system for case A1 PSS deactivated.

In the study considering the Svenska kraftnät model, several different assessments have been made. Some of the results can be compared with results from linearisation, which are presented in Figure 87. This is however only an approximate comparison, due to the limitations of the linearisation tool used (PSS SINCAL).

System model linearisation



List of eigenvalues

Mode	Frequency (f) [Hz]	Damping (ζ) [%]
1	0.28	4.1
2	0.42	5.3
3	0.76	1.9
4	0.80	5.2
5	0.90	3.2
6	1.09	3.4
7	1.29	5.5
8	1.54	5.1
9	1.94	6.5

Figure 87 Linearisation of the Svenska kraftnät model. Eigenvalue plot and detailed results presented in the table. These are only used for approximate comparison, due to the limitations of the linearisation tool used (PSS SINCAL).

First, several evaluations of a large disturbance in the form of a line trip have been made, using case D2 and D3. The line was tripped at t=40 s and corresponds to a line located in Sweden with an active power flow of about 420 MW before the trip. In addition, case D1 is used for evaluating the estimation of oscillatory modes from low levels of oscillations (or ambient data).

Case D2 is without noise, while cases D1 and D3 are with random walk noise on approximately 10% of the loads in the system. A comparison of the studied cases is presented in Figure 88.

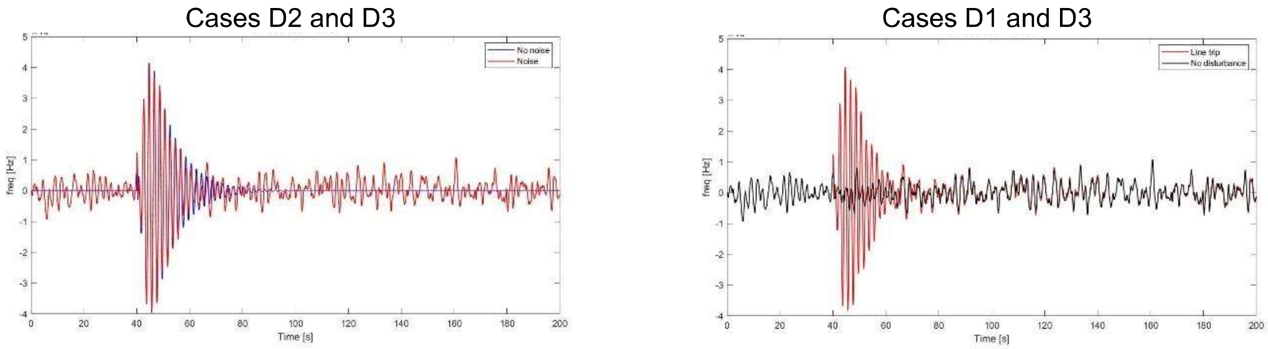


Figure 88 Time domain results showing frequency difference [mHz] between two buses, for Cases D2 and D3 (left) and D1 and D3 (right).

The frequency signal from two buses have been used for performing a visual approximation of the most dominant oscillations in case D2, presented on the rights side of Figure 89. The figure shows that there are 10 periods in approximately 20 seconds corresponding to a frequency of 0.5 Hz. Using the logarithmic decrement method to calculate the decay damping[75] results in a damping of approximately 3.2%.

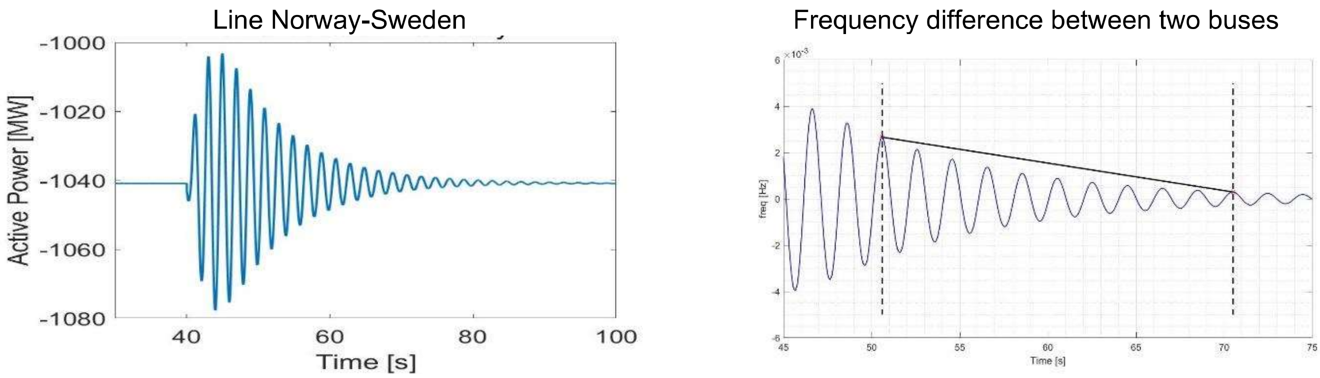


Figure 89 Time domain results for Case D2. Right: power flow on a line between Norway and Sweden, impacted by the trip of another line at t=40 s. Left: zoomed in frequency difference used to approximate the oscillation frequency and damping.

In the assessment of the application estimation results, different levels of PMU deployment have been addressed. In Table 12, results are presented based on a pre-selected set of 16 PMUs evenly distributed in the system for all three study cases. It can be noted that the most dominant oscillation, as estimated visually, is identified in all three cases.

[75] $n = 10$, $y_1 = 0.0027$, $y_{11} = 0.0003$

Table 12 Application estimates with 16 PMUs evenly distributed in the system. Visual identified results are included for comparison.

	Visual		Case D1 (no dist.w. noise)		Case D2 (w. dist.no noise)		Case D3 (w. dist.w. noise)	
Mode	**f [Hz]**	**ζ [%]**	**f [Hz]**	**f [Hz]**	**ζ [%]**	**ζ [%]**	**f [Hz]**	**ζ [%]**
1							0.21	5.8
2			0.37	3.2				
3			0.43	0.0				
4	0.5	3.2	0.52	4.8	0.5	3.4	0.5	3.9
5					0.6	7.7		
6			0.68	6.0				
7					0.74	9.0		
8			0.95	5.0			0.89	9.1
9			1.04	3.3				

The recursive mode tracking method was utilised for case D2 and D3, determining the mode shapes of the mode estimated presented in Table 12. For case D2, mode shapes for the 0.5 and 0.74 Hz modes are presented in Figure 90, while for case D3 the mode shapes of the 0.17, 0.5 and 0.89 Hz modes are presented in Figure 91. As can be seen, the 0.74 and the 0.89 Hz modes have completely different mode shape patterns, validating that these are correctly identified as different modes.

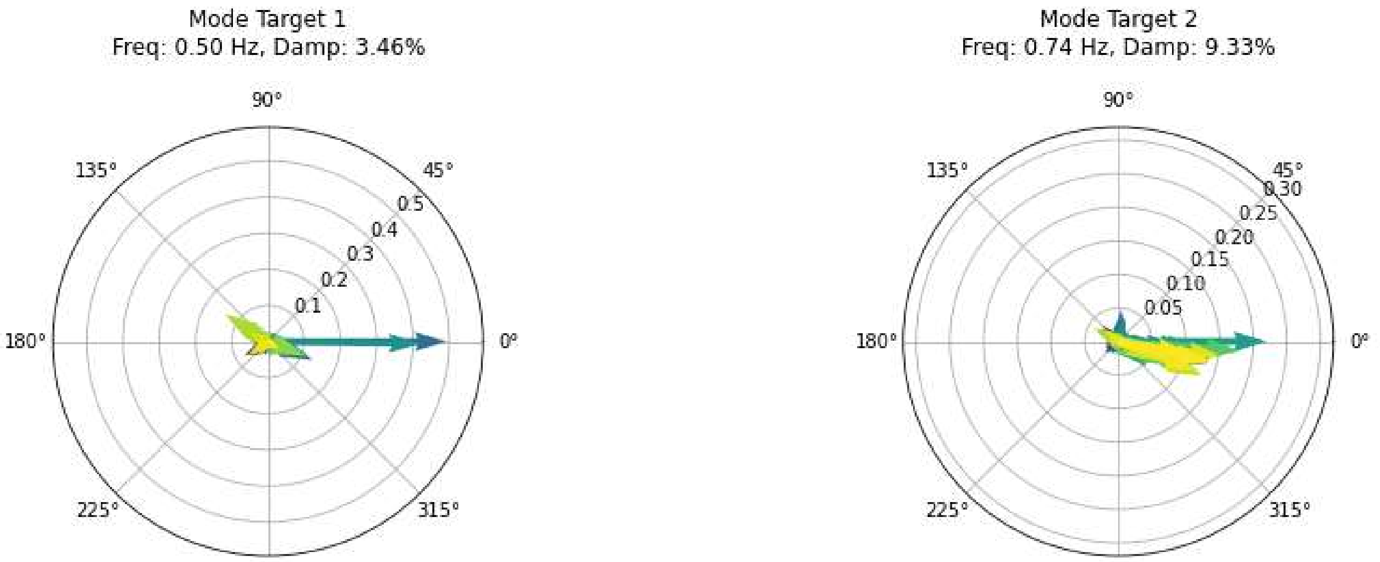


Figure 90: Mode shape plots of the Svenska kraftnät model for case D2, no noise.

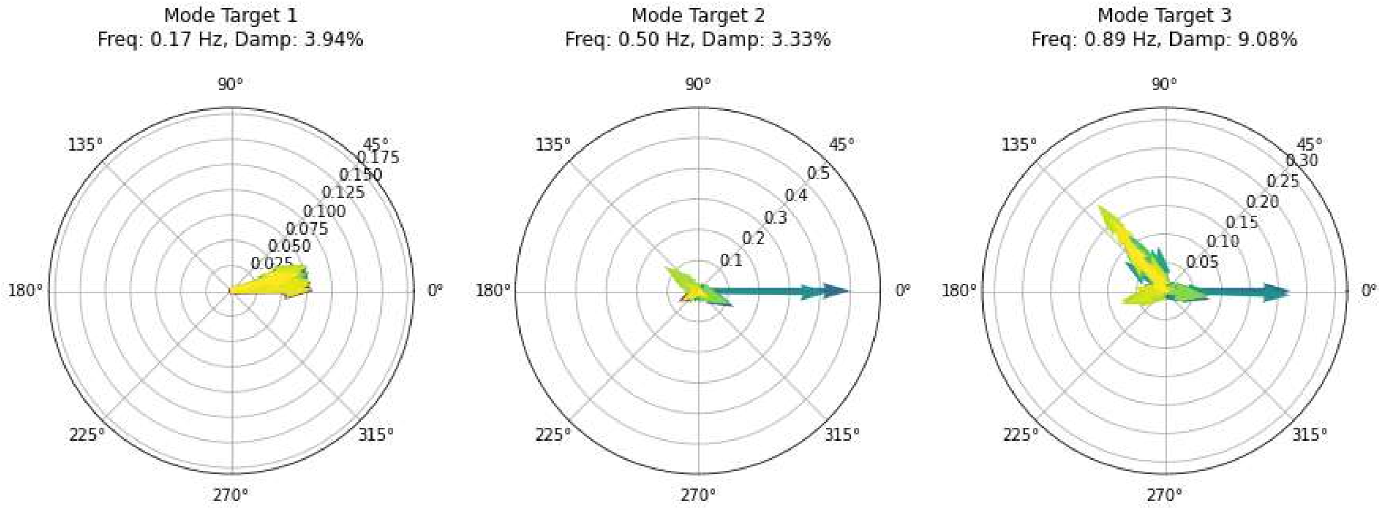


Figure 91: Mode shape plots of the Svenska kraftnät model for case D3, with noise.

Evaluating how the availability of PMUs influences the results, Table 13 presents the results for Case D3, for a decreasing number of PMUs. The highest number of PMUs used are 182, then 100 of these are selected randomly, and then 30 are selected randomly of the set of 100, etc. As can be seen in the table, uncertainty of estimation is generally increasing with decreased number of PMUs. Comparing the use of 16 PMUs distributed throughout the system, as presented in Table 12 with the use of 16 randomly selected PMUs, in Table 13, the quality of the estimates differs where in the latter case an additional negatively damped mode is estimated which is not present in the other sets.

Table 13 Application estimates for Case D3 (with noise), for different number of PMU signals. Linearisation results are included for comparison

	Linearisation		Case D3 (5 PMU)		Case D3 (16 PMU)		Case D3 (30 PMU)		Case D3 (100 PMU)		Case D3 (182 PMU)	
Mode	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**
1			0.21	3.9	0.21	5.8	0.20	4.9	0.21	4.6	0.20	4.6
2	0.28	4.1	0.32	7.9								
3	0.42	5.3	0.43	6.0			0.42	-0.8	0.41	1.7	0.42	3.2
4					0.5	3.4	0.5	1.3	0.5	1.9	0.50	2.3
5			0.5	-6.5	0.51	-3.2			0.51	1.2	0.52	2.2
6			0.58	9.5	0.58	8.1						
7	0.76	1.9										
8	0.80	5.2										
9	0.90	3.2			0.91	8.2	0.93	7.6	0.92	9.4	0.92	9.3
10									0.95	8.6	0.96	7.9
11	1.09	3.4			1.02	7.6						
12	1.29	5.5										
13	1.54	5.1										
14	1.94	6.5										

Figure 92 highlights the importance of tracking the mode shape over time. While the estimated frequencies of the two modes are quite similar—potentially leading to confusion as to whether they represent the same phenomenon—their mode shapes differ. These differences provide insights into the nature of the oscillations and help to distinguish closely spaced modes. Continuous tracking of the observed modes over time by the recursive method, enhances confidence in the accuracy of the identified mode and its classification

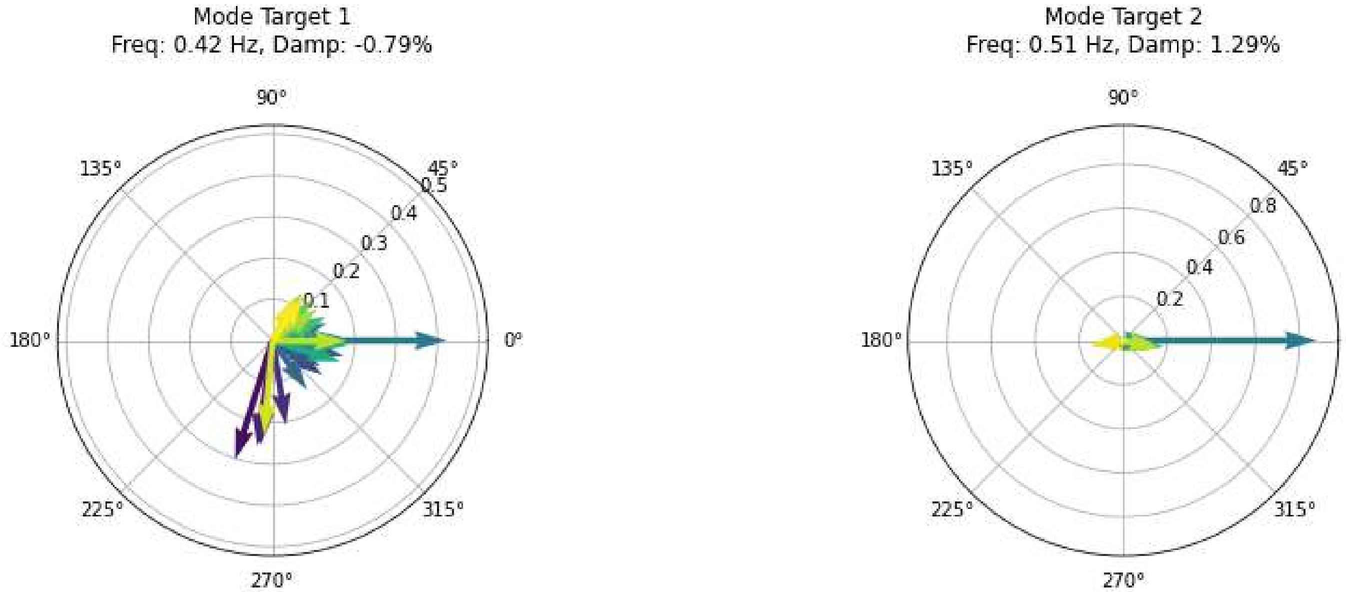


Figure 92: Mode shape plot of the Svenska kraftnät model for case D3 (30 PMU), highlighting the importance of classification for closely spaced modes.

Addressing the estimation results for a small signal disturbance in the Svenska kraftnät model is performed by considering cases C1 and C2. Here the small signal disturbance was applied by simulation of a 10 ms short-circuit applied at t=40 s. Case C1 is without noise, while case C2 is with random walk noise on approximately 10% of the loads in the system. Time domain results are presented in Figure 93 and Figure 93.

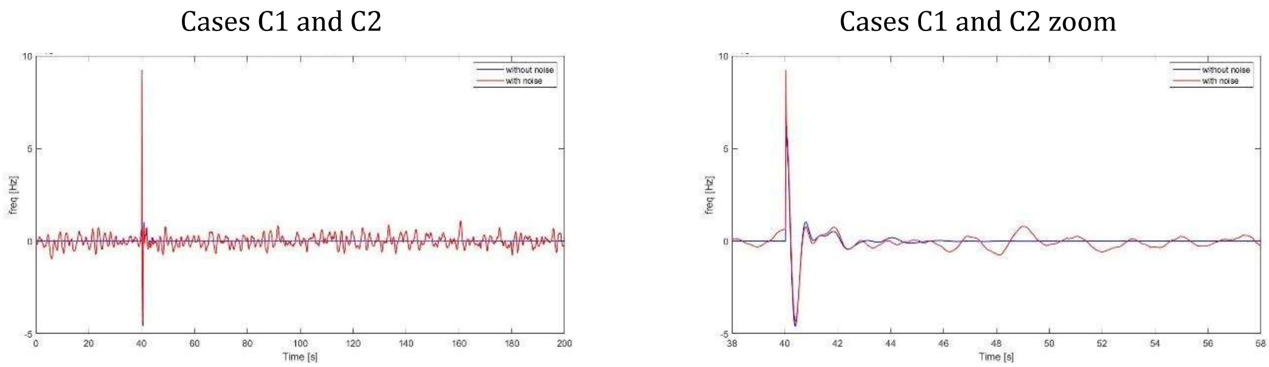


Figure 93 Time domain results showing frequency difference [mHz] between two buses, for Cases C1 (without noise) and C2 (with noise) with a zoomed in version to the right).

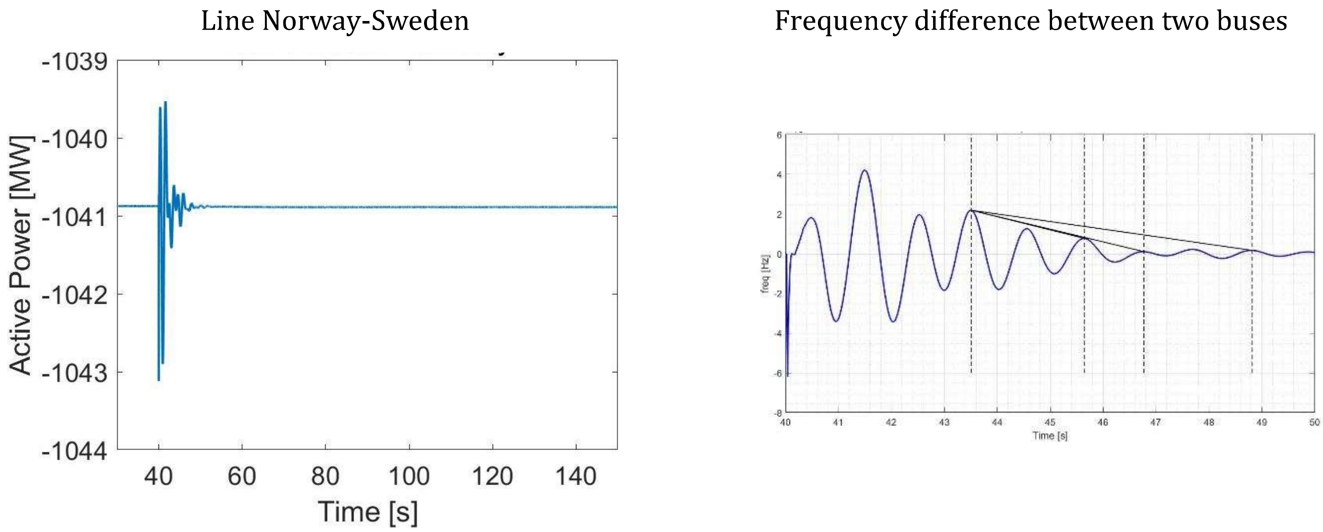


Figure 94 Time domain results for Case C1. Left: power flow on a line between Norway and Sweden, impacted by the trip of another line at t=40 s. Right: zoomed in frequency difference [mHz] used to approximate the oscillation frequency and damping.

Performing a visual approximation of the most dominant oscillatory frequency for case C1 is done using Figure 94. As several modes are present, the direct estimation is more complex, with the most dominant mode estimated to have a frequency of approximately 0.93 Hz and a damping between 5.5-11.8% depending on the time interval used for the estimation.

Application estimates for cases C1 and C2 are presented in Table 14, comparing the result with the linearised model, visual approximation, as well as with the application estimates for case D1 (only ambient data). Also here, results are based on a pre-selected set of 16 PMUs evenly distributed in the system for all three study cases. As this disturbance is very small, the application has difficulty to identify the oscillations in the system. For the cases with noise, results are rather similar with and without disturbance.

Table 14 Application estimates for Cases C1 (without noise) and C2 (with noise). Linearisation results, visual approximation and estimated for Case D1 (without disturbance with noise) are included for comparison.

	Linearisation		Visual		Case D1 (no dist. w. noise)		Case C1 (w. dist. without noise)		Case C2 (w. dist. w. noise)	
Mode	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**f [Hz]**	**ζ [%]**	**ζ [%]**	**ζ [%]**	**f [Hz]**	**ζ [%]**
1	0.28	4.1			0.37	3.2			0.30	0.0
2	0.42	5.3			0.43	0.0			0.41	4.8
3					0.52	4.8			0.51	3.2
4					0.68	6.0			0.67	8.2
5	0.76	1.9					0.73	7.7		
6	0.80	5.2								
7	0.90	3.2	0.93	5.5-11.8	0.95	5.0				
8	1.09	3.4			1.04	3.3			0.97	8.6
9	1.29	5.5								
10	1.54	5.1								
11	1.94	6.5								

To study the sensitivity of the application results, parameterisation and erroneous PMU data has been studied. Effects that different types of erroneous PMU data may have on the algorithm are listed in Table 15.

Table 15 Impact of erroneous PMU data on the oscillation detection algorithm.

Cause	Effect	Potential Mitigation Strategies
Outliers	Skewed estimation, leading to a misleading interpretation of system dynamics.	Use outlier detection algorithms to identify and remove anomalies.
Noise	Reduced numerical stability, making it harder to distinguish between significant modes and noise.	Apply filtering techniques to reduce noise.
Missing values	Interrupts the continuity of the time series, resulting in incomplete or biased estimates of system dynamics.	Use techniques for handling missing data.

Outliers, if they are of a high magnitude, can cause the algorithm to misinterpret the observability of the mode. This can lead to skewed results where the affected measurement dominates, making the modal shape representation show only the high-magnitude oscillation. The presence of outliers may indicate the location of a disturbance. For example, PMU measurement locations closer to a disturbance location are likely to show a greater amplitude. Identification of outliers is therefore useful for root cause analysis.

Excessive noise can obscure the damping estimates of the system's frequency modes, reducing the algorithm's ability to accurately capture dynamics. If too much noise is present, crucial information can be lost.

Missing values cause gaps in the modal shape plots, removing key components of the estimate. If the missing data corresponds to a significant contributor, the impact on the overall estimate will be much more severe than if a smaller contributor is missing.

Discussion and Conclusions

In this section, we have presented some of the result from a large set of tests performed to validate the developed monitoring applications based on simulated results using an open benchmark model as well as a large-scale model of the Swedish power system.

Estimation of frequency and damping of low damped modes is valuable to address the dynamic state of the power system, where a challenge lies in how to have reliable results in scenarios with low levels of oscillations.

Different deployment levels of PMUs have a direct influence on the mode estimation ability. A limited set of PMUs which are distributed throughout the system can be able to capture the critical oscillatory modes of the system. However, identification of local modes may require utilisation of higher number of PMUs.

4.4 Forced oscillations and resonances detection

This section focuses on identification and assessment of forced oscillations in power systems. Several commonly used methods for detecting forced oscillations are presented and evaluated based on their accuracy in estimating the forced oscillation frequency. Furthermore, a method for distinguishing between forced and natural oscillations is proposed and validated.

4.4.1 Introduction

Contrary to natural oscillations which are an inherent characteristic of any dynamic system, forced oscillations are caused by an external periodic source continuously exciting the system dynamics. Since forced oscillations are due to an external source, characteristics such as frequency and waveform are governed by the source and not by the system dynamics as is the case for natural oscillations.

4.4.2 Theory and methods

Definition

Forced oscillations can have many waveforms, such as triangle wave, sawtooth, and square wave. Since the oscillation is assumed to be periodic it can be described as a Fourier series with harmonics of the oscillation frequency [76].

$$f(t) = \sum_{m=1}^{\infty} 2|A_m| \sin(k\omega_0 t + \phi_m) = \sum_{-\infty}^{\infty} A_m e^{jm\omega_0 t}$$

Where A_m is the amplitude of component m, ϕ_m is the phase angle of component m, and t is the time.

Many possible sources of forced oscillations have been reported in the literature. Possible sources include cyclical loads, low-speed diesel generators, poorly tuned generator control systems, such as Power System Stabilizers (PSSs), malfunctioning steam valves in thermal generators, hydro turbines operating in the rough zone, and poorly tuned control systems for wind power plants. A comprehensive summary of forced oscillation sources is given in [77].

Resonance

If the frequency of a forced oscillation is very close to a system mode, resonance between the forced oscillation and the system mode can occur.

The amplification of the resonance with the system mode could be significant if the following conditions are fulfilled [78]:

1. Frequency of the forced oscillation must be close to that of a system mode.
2. The system mode must be poorly damped.
3. The forced oscillation must be in a location where there is a high controllability of the system mode.

If all three conditions are fulfilled the amplitude of the resulting oscillation could be greatly amplified and it could be observed in large parts of the power system. However, it is not always required that all three conditions are fulfilled to still have significant amplification of the oscillation due to resonance. Such an event occurred in the USA on January 19, 2019[79] when a malfunctioning steam turbine in Florida gave rise to a forced oscillation with frequency close to that of a well-known inter-area mode. This caused system-wide oscillations in the Eastern Interconnection. In this case, two out of three conditions for resonance were fulfilled; the frequency of the forced oscillation was close to a system mode, and the forced oscillation occurred in a location where the system mode was highly controllable. However, the system mode was well-damped in this situation.

Effect of forced oscillations on estimation of electromechanical modes

As mentioned in the previous section, forced oscillations are not governed by the system dynamics in the same way as natural oscillations are. Instead, they inherit their characteristics, such as frequency and waveform,

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[76] R. Xie and D. J. Trudnowski, "Distinguishing between natural and forced oscillations using a cross-spectrum index," in 2017 IEEE Power.

[77] M. Ghorbaniparvar, "Survey on forced oscillations in power system," Journal of Modern Power Systems and Clean Energy, vol. 5, no. 5, pp.671–682, 2017.

[78] S. A. N. Sarmadi and V. Venkatasubramanian, "Inter-area resonance in power systems from forced oscillations," IEEE Transactions on Power Systems, vol. 31, no. 1, pp. 378–386, 2016.

[79] NERC, "Eastern interconnection oscillation disturbance, January 11, 2019 forced oscillation event," Report, 2019.

from its source. Since the source is continuously exciting the system at the forced oscillation frequency, it will appear as an undamped oscillation in PMU measurements.

Numerous mode meter algorithms have been developed for estimating system modes using PMU measurements, e.g. the SSI method described in previous sections. These algorithms are generally not designed to operate in the presence of forced oscillations and give biased results if a force oscillation is present[80]. Depending on the amplitude and frequency of the forced oscillation, the estimated mode damping and frequencies can be biased due to the forced oscillation, which will give an incorrect assessment of the system stability margins. In addition, the mode meters can report the forced oscillation as an undamped system mode. It is therefore an important feature of a mode meter to be able to distinguish between natural and forced oscillations.

Distinguishing between forced and natural oscillations

As established in the previous section, it is important to be able to distinguish between forced and natural oscillations. If the oscillation is due to a poorly damped natural mode, the system is close to a stability limit and there is a risk of the system becoming unstable, in which case it is important to take remedial actions to improve the damping of the affected system mode. Whereas, if the oscillation is forced the system is not necessarily close to any stability limit. The challenge in classifying an oscillation as forced or natural is that forced oscillations look very similar to undamped natural oscillations in PMU measurements, even though undamped natural oscillations are very rare they could still occur. The task of distinguishing them becomes even more challenging if the frequency of the forced oscillation is close to a system mode, then the PMU measurements are dominated by the system mode instead.

4.4.3 Developments

Detection of forced oscillations

The previous sections give a motivation to why it is important to be able to detect forced oscillations. In [81], the accuracy of three currently available methods for detecting forced oscillations were evaluated. The included methods were SSI, a spectral method using Welch periodograms, and the self-coherence method.

The 11-bus, two area system illustrated in Figure 96 was used for the evaluation. Three cases were simulated using the simulation software Simpow. In Case 1 the frequency of the forced oscillation was the same as the inter-area mode, in Case 2 the frequency of the forced oscillation was lower than the inter-area mode frequency, and Case 3 consisted of a natural oscillation caused by disconnecting part of the load at a bus for a short time. The detection methods were then evaluated on how accurately they estimated the frequency of the oscillation. The SSI method is also able to estimate the damping. In Case 1 the frequency of the forced oscillation was the same as the inter-area mode, in Case 2 the frequency of the forced oscillation was lower than the inter-area mode frequency, and Case 3 consisted of a natural oscillation caused by disconnecting part of the load at a bus for a short time. The detection methods were then evaluated on how accurately they estimated the frequency of the oscillation. The SSI method is also able to estimate the damping.

The conclusions of the study were that all three methods were able to accurately detect a forced oscillation, even when it occurred at the same frequency as that of the inter-area mode. The SSI method detected both the inter-area mode and the forced oscillation even when the forced oscillation occurred at the same frequency as

[80] U. Agrawal, J. Follum, J. W. Pierre, and D. Duan, "Electromechanical mode estimation in the presence of periodic forced oscillations," IEEE Transactions on Power Systems, vol. 34, no. 2, pp. 1579–1588, 2019.

[81] D. Bergman, R. Eriksson and M. G. Alavijh, "Evaluation of Forced Oscillation Detection Methods," 2023 IEEE PES Conference on Innovative Smart Grid Technologies - Middle East (ISGT Middle East), Abu Dhabi, United Arab Emirates, 2023, pp. 1-5, doi: 10.1109/ISGTMiddleEast56437.2023.10078535.

the inter- area mode, although with a small increase in estimation error. The average error tended to increase when there was only partial PMU observability. For the spectral method using Welch periodograms, the selection of PMU measurement locations can have an impact on the results.

Distinguishing methodology

A methodology to distinguish between forced and natural oscillations was proposed in [82]. The method leverages the fact that forced oscillations do not exhibit damping in the same way as natural oscillations do. The method fits a Least Squares Autoregressive Moving Average plus Sinusoid (LS-ARMA+S) [83] model to the measurement data. The LS-ARMA+S model was selected because it can accurately separate an oscillation from the coloured background noise without losing the modal information contained in the noise at the oscillation frequency. The damping ratio is then used to classify the oscillation as forced or natural by comparing the estimated damping from the measurement data with the estimated damping from the background noise. Figure 95 shows a flowchart of the method, and the different steps are explained below.

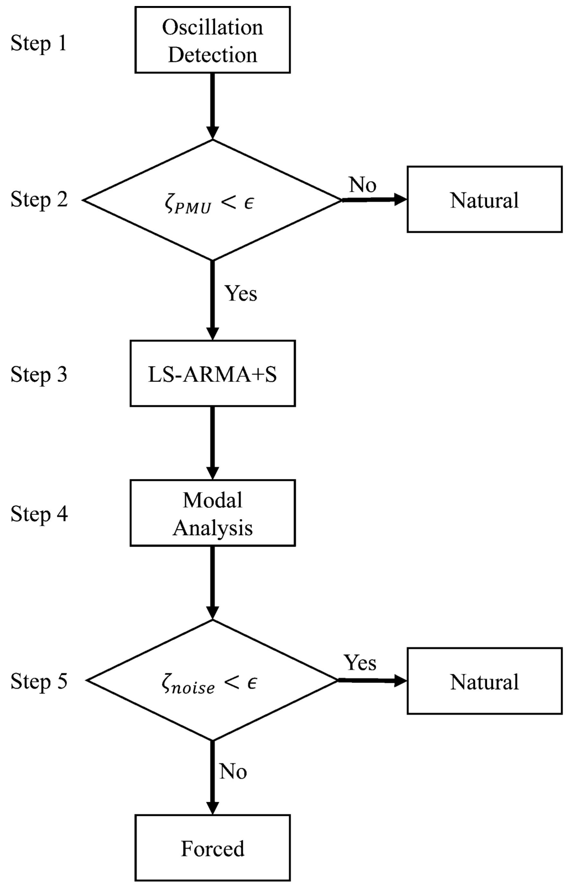

Figure 95: Flowchart of the proposed oscillation classification methodology.

[82] D. Bergman, R. Eriksson and M. Ghandhari, "Initial Results in Distinguishing Between Forced and Natural Oscillations Using PMU Data," 2024 International Conference on Smart Grid Synchronised Measurements and Analytics (SGSMA), Washington, DC, USA, 2024, pp. 1-6, doi: 10.1109/SGSMA58694.2024.10571517.

[83] J. Follum, J. W. Pierre, and R. Martin, “Simultaneous estimation of electromechanical modes and forced oscillations,” IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3958–3967, 2017.

Step 1: An oscillation is detected by a suitable method, and the frequency and damping ratio of the oscillation mode is calculated.

Step 2: If the damping ratio ζ_{PMU} is larger than some small damping threshold, ϵ, the oscillation is classified as a damped natural oscillation. Conversely, if the damping ratio ζ_{PMU} is less than ϵ it cannot be excluded that the oscillation is forced, the algorithm then moves on to step 3.

Step 3: The LS-ARMA+S algorithm is run with the calculated oscillation frequency from step 1 as input to the sinusoidal part of the method. This step separates the undamped sinusoidal component from the background noise.

Step 4: When an ARMA model has been fitted to the background noise, the electromechanical modes are extracted from the parametric model, which only contains modal information of the background noise

Step 5: The damping ratio, ζ_{noise}, of the corresponding mode in the background noise is extracted. If ζ_{noise} is larger than ϵ it means that the mode exhibits positive damping even though it appears undamped in the PMU data, it must therefore be some source driving the oscillation and it is therefore classified as forced. Conversely, if ζ_{noise} is smaller than ϵ it means that the mode exhibit very poor damping also in the background noise and it is then concluded that the oscillation is natural.

4.4.4 Validation

The concept of the proposed distinguishing method was tested in two case studies. In the first case study a simple transfer function was used to represent a simple test system

$$G(s) = \frac{2}{s + 0.2 + j2\pi 0.4} + \frac{2}{s + 0.2 - j2\pi 0.4} + \frac{2}{s + 1.5 + j2\pi 1.1} + \frac{2}{s + 1.5 - j2\pi 1.1}$$

The transfer function above has two oscillatory modes at frequencies 0.4 Hz and 1.1 Hz. A forced oscillation is implemented as a sinusoidal input to the system.

$$f(t) = A\cos(2\pi f_{FO} t)$$

Where A is the amplitude of the forced oscillation and f_{FO} is the forced oscillation frequency. An undamped natural oscillation is created by adjusting the real part of the 0.4 Hz mode in the transfer function above so that the damping becomes 0.008%. The oscillation is then started by applying a step to the input of the transfer function. The step function or forced oscillation function is added to a vector of white Gaussian noise and the resulting signal is used as input to the transfer function system.

In the second study the commonly used two-area test system shown in Figure 96 is used.

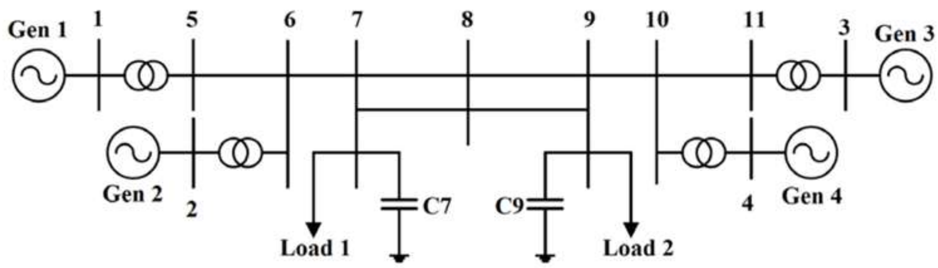

Figure 96: The Kundur two-area test system

The two-area system has one inter-area mode and two local modes. For the case with a forced oscillation, the damping ratio of the inter-area mode is adjusted so that it is approximately 5 %, and for the case with a natural oscillation, the damping ratio of the inter-area mode is adjusted so that it is approximately 0 %. To model random load changes a small part of the loads at buses 7 and 9 have been modelled as white Gaussian noise. The bus frequencies at buses 5-11 have been used in the distinguishing methodology. Further details on the simulations can be found in [84].

Results

1000 simulations were performed using the transfer function system with a natural or forced oscillation randomly selected. Figure 97 and Figure 98 show the distribution of damping ratio estimates from the LS-ARMA+S algorithm.

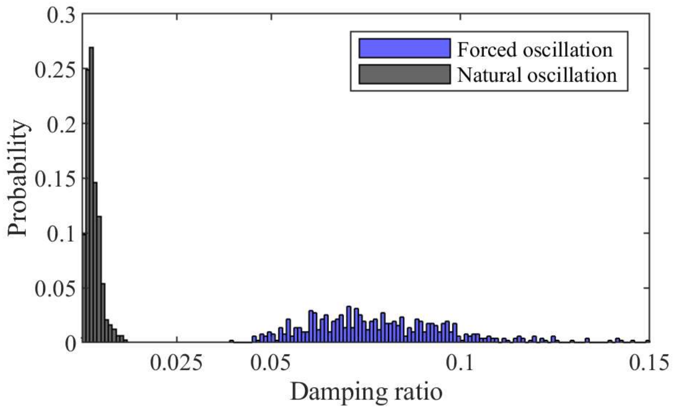

Figure 97: Distribution of the damping estimates for forced and natural oscillations when the forced oscillation is not visible in the measurement data.

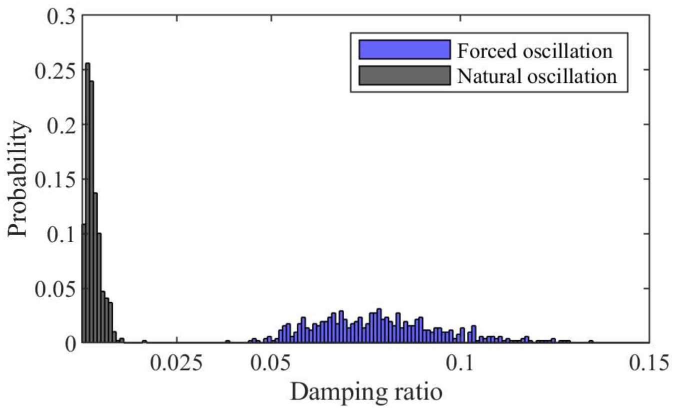

Figure 98: Distribution of the damping estimates for forced and natural oscillations when the forced oscillation is visible in the measurement data.

[84] D. Bergman, R. Eriksson and M. Ghandhari, "Initial Results in Distinguishing Between Forced and Natural Oscillations Using PMU Data," 2024 International Conference on Smart Grid Synchronised Measurements and Analytics (SGSMA), Washington, DC, USA, 2024, pp. 1-6, doi: 10.1109/SGSMA58694.2024.10571517.

An important parameter to set in the distinguishing methodology is the damping threshold. Figure 97 and Figure 98 illustrate that if the threshold is selected carefully, in this case is set to 2.5 %, the oscillation can be classified correctly in 99.9 % of the 1000 simulations.

In the two-area test system a classification of the oscillation is calculated for each of buses 5-11 using the bus frequency as input. When the oscillation is forced, the method correctly classifies the oscillation as forced at all buses except at bus 7. The reason for this anomaly is yet to be determined. When the oscillation is natural the method correctly classifies the oscillation as natural at all included buses.

4.4.5 Validation on the Nordic 44 test system

The proposed method was also validated using the Nordic 44 test system. Simulation data for three test cases was generated by the PSS/E simulations framework utilised for the NEWEPS Test & Demonstration platform. Two of the test cases contained a forced oscillation and one case contained a poorly damped natural oscillation. In Case 1 the frequency of the forced oscillation is close to a system mode, in Case 2 the frequency of the forced oscillation is not close to a system mode, and in Case 3 a poorly damped natural oscillation is obtained by turning off the PSS:s on the generators and applying a step change on a generator. The frequency of the forced oscillations was unknown beforehand. Frequency, in the form of emulated PMU data, from 10 buses distributed in the system was provided as input to the classification algorithm. An example of the frequency for one of the cases is shown in Figure 99. The data has been high-pass filtered to remove low-frequency trends.

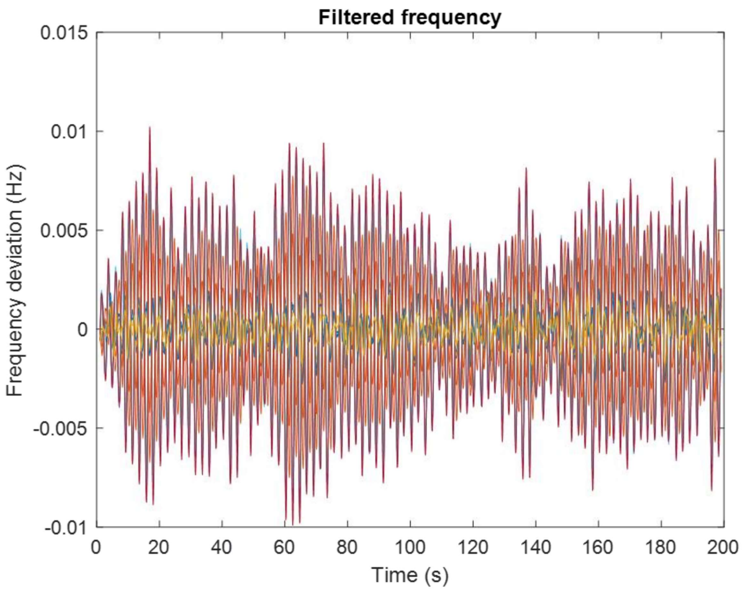

Figure 99 Simulated frequency from 10 buses in the Nordic 44 test system

Welch's method is used to detect the oscillation and to obtain an initial frequency estimation. All measured buses where the amplitude at some frequency in the frequency spectrum exceeds a certain threshold, here it is set to $2 \cdot 10^{-5}$, is selected, see Figure 100 for an example. The frequency data at all measured buses that exceed the threshold was then fed into the classification algorithm. The results for the three cases are shown in Figure 101 - Figure 103. The estimated frequency and damping at each bus are shown as a "+" in the Figures. The "*" symbol shows the frequency and damping estimate from a conventional mode meter. As can be seen from Figure 101 and Figure 103 the estimated damping of the system mode is biased towards zero when in fact the system mode is well damped. The results for Case 1 show that the Welch's method is able to correctly classify the oscillation as forced. For Case 2 the method is also able to classify the oscillation as forced. However, at some buses the method selects the frequency of the system mode (approx. 0.45 Hz) instead of the forced oscillation which appear to be around 0.9 Hz. Thus, there are still more work needed to improve on the classification method. Finally, for Case 3 the method is able to correctly classify the oscillation as natural.

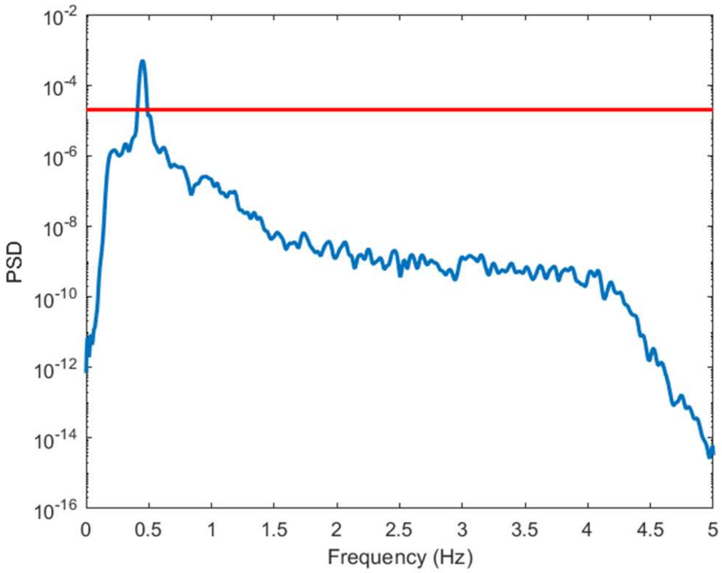

Figure 100: Example of frequency spectrum for simulation data from one bus. The threshold for oscillation detection is marked by the red horizontal line.

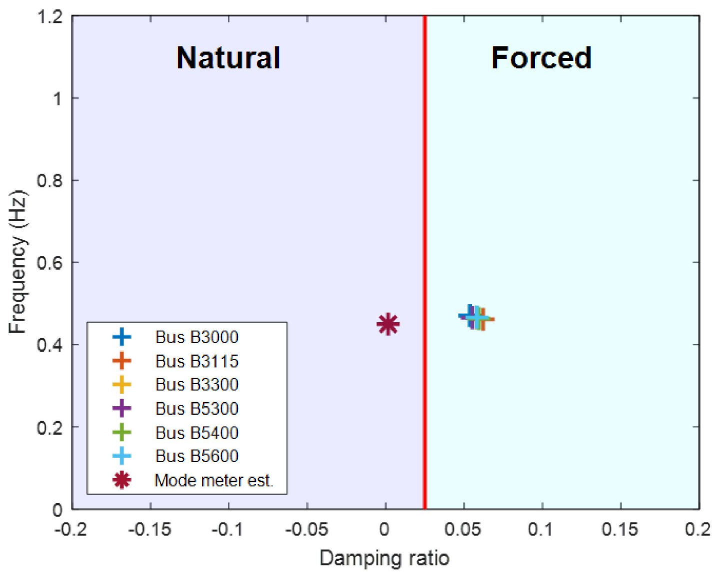

Figure 101: Case 1 classification results. This case contains a forced oscillation.

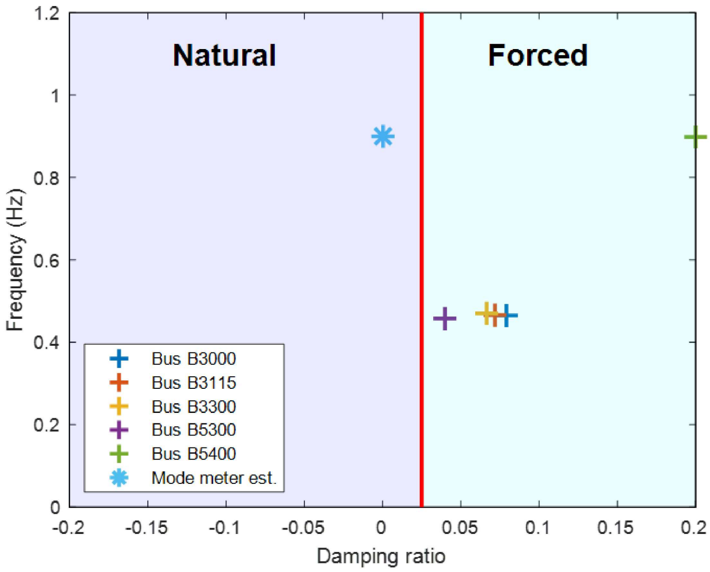

Figure 102: Case 2 classification results. This case contains a forced oscillation.

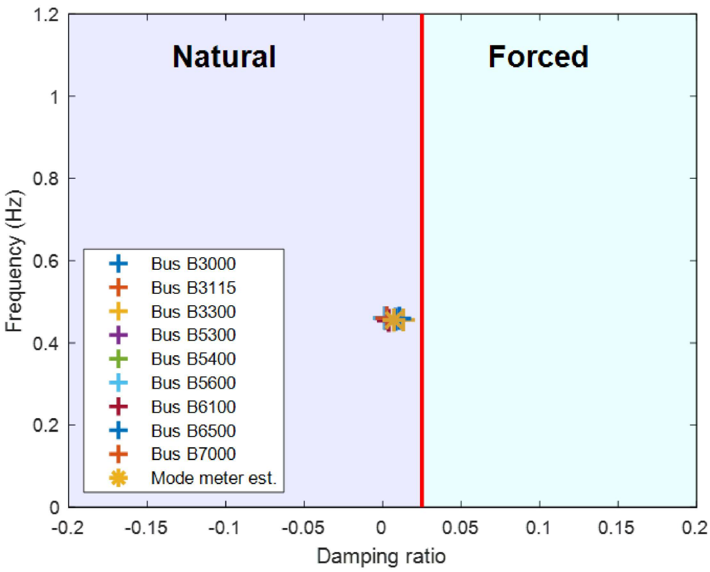

Figure 103: Case 3 classification results. This case contains a poorly damped natural oscillation.

4.5 Summary

Solutions for wide-area monitoring enable the operator to become aware of the dynamic behaviour of the power system. This increased situational awareness is an important factor for operation of the future power system, where system dynamics are foreseen to be of increased importance for example due to challenges related to the change in the generation mix. The methods presented in this chapter include voltage stability monitoring, monitoring and detection of natural oscillations, and detection of forced oscillations and resonances.

The developments regarding the voltage stability monitoring have involved the assessment of several voltage stability indicators, including AA, AD, SZI, and NLI. During the work, the SZI method has been further developed with a novel approach and is seen as a valuable voltage stability indicator. Regarding natural oscillations, the development work has focused on the SSI method to detect low damped oscillations. The ability to monitor and track the oscillations is enhanced through the development of clustering techniques.

Both the voltage and oscillation monitoring methods have been developed into applications which are deployed in the NEWEPS Test & Demonstration platform, where they have been further tested and validated.

The classification of oscillations as forced or natural is an important factor when addressing both how to present the information to the operator, and which mitigating methods that should be taken. The developed method to correctly classify forced oscillations includes an LS-ARMA+S model and has been tested and validated utilising files created for the NEWEPS Test & Demonstration platform.

The work presented in this chapter provides important insights in the detection of dynamic phenomena, and how WAMS applications can be integrated, tested and validated utilising the NEWEPS Test & Demonstration platform.

5 WAMPAC Solutions

5.1 Introduction

Besides monitoring of the system's dynamic behaviour, the NEWEPS project lifts up the importance of further developing efficient methods for securing the system's post-contingency operation by identification of the most suitable of corrective, remedial actions that can be deployed. Corrective, remedial actions are commonly used to secure the system operation as a part of System (Integrity) Protection Schemes (SIPS). SIPS are often designed to allow the system operation beyond N-1 criteria by, if needed, returning the post-contingency system operating point within a secure region with the help of these remedial actions. Having a predefined cyber-physical design, SIPS deploy predefined set of remedial actions when they detect that certain tracked system quantity reaches a threshold e.g. goes outside of the operating limits. Besides a predefined design, SIPS often have parameters that can be adjusted to the current operating situation, e.g. threshold values for deployment of remedial actions and selecting a subset of predefined remedial actions and their extent. Appropriate settings of these adjustable SIPS parameters have been analysed in the previous ASAP project[85]. From the results of the ASAP project, the solution presented in this chapter extends the use of corrective actions beyond predefined cyber-physical design of SIPS starting from the following assumptions:

- each contingency can be detected as an event by the centralised monitoring system
- in the event of a contingency, the centralised system can deploy a specific set of corrective actions that are tailored to the current operating point and to the particular contingency
- selection of the corrective actions is not subject to a cyber-physical design of the SIPS-alike triggering scheme i.e. centralised monitoring and control system allows the set of corrective actions and power system elements included in them to be freely chosen in real-time.

With respect to the aforementioned assumptions, the algorithm presented in this chapter finds the corrective actions that can in the most efficient and cheapest way secure a post-contingency operation of the system. The proposed method is integrated as an independent application into the NEWEPS Test & Demonstration platform (described in detail in chapter 3).

5.2 Optimisation of corrective actions

The flow chart of the algorithm for calculating optimal corrective actions for the N-1 secure post-contingency operation of the system with respect to the previously mentioned assumptions is given in Figure 104. The algorithm takes input from the NEWEPS Test & Demonstration platform in the form of:

1. **Current operating point**: this point is defined by the snapshot of generation and consumption, and voltage profile. The necessary information to construct the current operating point is active power output/input and reactive power/voltage set-point of generators/loads. If some of this data is unavailable, it is provided by the NEWEPS Test & Demonstration platform state estimator.
2. **System model data**: static system parameter data including line impedances, parameters of dynamic generator and load models, controllers as well as system state limits e.g. bus voltage limits, line current limits, internal generator states limits defining its capability.
3. **Contingency list**: predefined list of the contingencies that system might experience. This list might contain contingencies affecting all the system elements or a shortened, predefined list of the most-

[85] ASAP (Advanced System protection schemes Applied in the Power grid): https://prosjektbanken.forskningsradet.no/en/project/FORISS/327728

probable events (for reducing computational effort of the algorithm, common in a legacy practice). The contingency list contains basic information on type of contingency and identity of the faulted component.

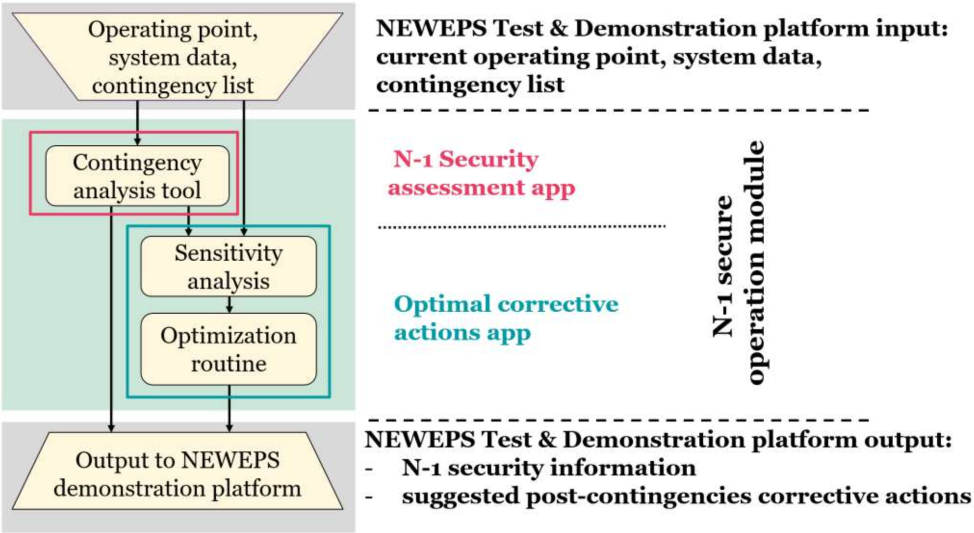

Figure 104: Flow-chart of the algorithm for finding optimal corrective actions

The listed input information is fed to the WAMPAC solution "**N-1 secure operation module**" containing two independently executed applications:

1. **N-1 security assessment app**: the main purpose of this app is to assess the post-contingency security of the system when subjected to the events from the contingency list. The main part is the contingency analysis tool described later in this chapter. The output provides information on which contingencies that result in a non-secure post-contingency operation and give further information on which operating limits that have been jeopardised.
2. **Optimal corrective actions app**: based on the current system operating conditions, calculates the optimal corrective actions to secure a post-contingency system operation. "Optimal" can here be used in multiple contexts depending on the particular needs of the operator, some of them being "the cheapest" or "the most robust". The application contains two parts: sensitivity analysis tool and optimisation routine tool. The sensitivity analysis calculates a subset of corrective actions that are the most effective in securing the system operation after the particular "critical" contingency. This subset is forwarded to the optimisation routine which, together with the system model and the list of "critical" contingencies (provided from the N-1 security assessment app) and the current operating point, creates an SCOPF-like optimisation model. The solution of the optimisation routine then gives optimal corrective actions.

The N-1 secure operation module, with its two applications, calculates and outputs the following information further to the NEWEPS Test & Demonstration platform:

- List of "critical" contingencies with information on jeopardised system operating limits. A critical contingency is hereby considered a contingency that leads to unsecure post-contingency operation of the system.
- List of corrective actions tailored to each critical contingency that needs to be deployed to secure the system in post-critical contingencies states.

The list of critical contingencies is directly fed to the NEWEPS Test & Demonstration platform from the N-1 security assessment app. As the same list is needed to calculate the optimal corrective actions, it is also fed into the Optimal corrective actions app, which calculates and outputs these actions to the NEWEPS Test & Demonstration platform. More detailed description of the aforementioned applications and their tools are provided in the following subsections.

5.2.1 Contingency analysis tool

For the purpose of use in the NEWEPS Test & Demonstration platform, a contingency analysis tool fully implemented in Python has been developed. The tool carries out steady state contingency analysis taking into account also stability through static stability indicators.

The tool starts the analysis by finding a steady state post-contingency operating point for all the events from the given contingency list. To find the post-contingency operating point, for each contingency a steady state system model is created in *Python Pyomo.* The model takes into account the following system characteristics:

- Steady state network model
- Steady state equivalent of generator dynamic model
- Generator governor control
- Generator excitation control
- Generator excitation limiters (results in switching between constant U and constant Q control)
- Generator prime mover limit (results in minimum and maximum generator active power output)
- Generator armature current limit (results in switching between constant U and constant Q control)
- Generator rotor current limit (results in switching between constant U and constant Q control)
- Generator static stability limit (results in switching between constant U and constant Q control)
- Load voltage dependency (static ZIP load models)

After finding a steady state post-contingency operating point for each contingency, the tool checks if the point lies in a secure-operation area. The secure operation area is, beside the system physical characteristics (reflected in the steady state system model), defined by the system operating limits. The system operating limits implemented in the tool are:

- Line loading limits
- Bus voltage limits
- Bus voltage stability limits based on the sensitivity indicator SZI described in chapter 4.2.

It should be observed that the secure operation area is in practice also constrained by other limits, e.g. small-signal stability limits. The developed contingency analysis tool may be expended by taking into account additional stability limits if they are expressed through a static indicator (similarly as the SZI voltage indicator).

If the post-contingency operating point lies outside of the previously described secure operation area, a contingency leading to that post-contingency state is added to the list of "critical contingencies". Together with the list of critical contingencies, the tool outputs corresponding information on the non-secure post-contingency state: identity of the operating limit being jeopardised and the extent of the limit violation. This information is used in the optimal corrective actions app besides being communicated to the NEWEPS Test & Demonstration platform for operator visualisation.

5.2.2 Choosing the most effective corrective actions (Sensitivity analysis)

The first step in securing the post-contingency operation of the system is to find out which corrective actions are the most effective in alleviating the identified problems, i.e. which corrective actions can at the lowest cost return the operating point within a secure operating area. For an example, if contingency k results in a post-contingency voltage at bus i below its minimum value $U_i < U_i^{(\min)}$, to secure the system operation a corrective action that affects system parameter p have to be applied such that $U_i > U_i^{(\min)}$. For the chosen corrective action to be the most effective, the change in voltage U_i must be the most sensitive to a change in parameter p.

To find such system parameter p (and corresponding corrective action affecting it) a sensitivity analysis can be carried out. The objective of the sensitivity analysis is to determine and rank system parameters p, affected by available corrective actions, with regards to how sensitive the change of function of interest $\eta_{kq}(p,x)$ is to p. The function of interest $\eta_{kq}(p,x)$ should reflect the sensitivity of system quantities q that lie outside of operational limits to parameter p. Besides parameter p, $\eta_{kq}(p,x)$ depends also on system states x. Examples of $\eta_{kq}(p,x)$ with respected to the system quantities q are given in Table 16.

Table 16: Examples of function $\eta_{kq}(p,x)$ with respect to different system quanitities

System quantity q	$\eta_{kq}(p,x)$
Line i-j loading (apparent power)	$\lvert S_{ij} \rvert$
Bus i voltage	U_i
Bus i voltage sensitivity indicator SZI	U_i

It should be noted that function $\eta_{kq}(p,x)$ is in general different for every different contingency k and its corresponding post-contingency state of the system (therefore index k in η_{kq}). In addition, in the post-contingency state there might exist more than one system quantity whose value lies outside the operating limits. In this case we can define function $\eta_k(p,x)$ as:

$$\eta_k(p,x) = \sum_{q \epsilon Q_k} \xi_q \eta_{kq}(p,x)$$

where Q_k is set of all system quantities that lie outside of the operating limits after contingency k occurs. Weight coefficient ξ_q gives an option to distinguish between importance of certain system quantities over the others. For example, by selecting appropriately ξ_q the operator might lift up the importance of keeping some of the system quantities inside operating limits compared to the others.

With $\eta_k(p,x)$ defined for each critical contingency k, sensitivities of this function to the change of parameters p can be calculated by linearizing the system around the operating point:

$$\frac{\boldsymbol{d\eta_k(p,x)}}{\boldsymbol{dp}} = \sum_{q \epsilon Q_k} \xi_q \frac{\boldsymbol{\partial \eta_{kq}(p,x)}}{\boldsymbol{\partial p}} + \sum_{q \epsilon Q_k} \xi_q \frac{\boldsymbol{\partial \eta_{kq}(p,x)}}{\boldsymbol{\partial x}} \frac{\boldsymbol{dx}}{\boldsymbol{dp}}$$

The bolded terms in the equation above are matrices. Matrix $\frac{\boldsymbol{dx}}{\boldsymbol{dp}}$ contains power system characteristics i.e. sensitivity of the system states $\boldsymbol{x}$ to the change of parameters $\boldsymbol{p}$. $\frac{\boldsymbol{dx}}{\boldsymbol{dp}}$ can directly be obtained from the systems' Jacobian matrix available from the solution of the contingency analysis tool reducing numerical burden of the whole algorithm.

The available corrective actions can be ranked with respect to their effectivity by comparing absolute values of sensitivities $\frac{\boldsymbol{d\eta_k(p,x)}}{\boldsymbol{dp}}$. The corrective actions which affect parameters $\boldsymbol{p}$ with the highest absolute value of $\frac{\boldsymbol{d\eta_k(p,x)}}{\boldsymbol{dp}}$ are in the context of linearised analysis the most effective to correct the set of system quantities Q_k. Based on the values of $\frac{\boldsymbol{d\eta_k(p,x)}}{\boldsymbol{dp}}$ it is now possible to sort available corrective actions on their effectiveness.

From here, the algorithm choses ϕ percent of the most effective actions to be considered in the later optimisation routine as so-called decision variables. The choice of ϕ determines a number of degrees of freedom for the optimisation routine. With less degrees of freedom, the optimisation routine would try to find solution with smaller number of corrective actions, possibly a simpler option for the system operator. However, smaller number of corrective actions does not mean cheaper overall costs. With more degrees of freedom (higher ϕ and more corrective actions in consideration) the optimisation routine will have larger search space which can allow the routine to find cheaper overall solutions. However, these solutions might be more complex for the operator to apply i.e. higher number of corrective actions, their types and locations. To summarise, the choice of ▯ and its effect on the solution for corrective actions is:

- Higher ϕ – more complex solution for the set of corrective actions C_a -> generally less overall system costs
- Lower ϕ – simpler solution for the set of corrective actions C_a -> might results in higher overall system costs

In this project, the choice of ϕ is left to the operator, but future implementations may include software solution that may automatically select ϕ depending on the current system situation and the wish list of the system operator.

5.2.3 Optimisation routine

Having found the set of most effective corrective actions C_a from the sensitivity analysis, the next step would be to calculate their extent that returns the system into a secure operating area. To do so, the optimisation routine tool creates a nonlinear optimisation model based on the following input:

- Current operating point (provided directly from the NEWEPS Test & Demonstration platform)
- System model data (provided directly from the NEWEPS Test & Demonstration platform)
- List of critical contingencies (obtained from the N-1 security assessment app)
- Set of candidates for corrective actions for each post-contingency state (obtained from the sensitivity analysis tool as a set of most effective corrective actions)

The optimisation model incorporates the dynamic system model for steady state with the same modelling considerations as in the contingency analysis tool. To assure that the solution is in the secure operating area, the optimisation model adds additional constraints reflecting operating limits of the system. The implementation includes the following limits (with the option for extension in the future):

- Line loading limits
- Bus voltage limits
- Bus voltage stability limits based on the sensitivity indicator SZI described in chapter 4.2.

A set of candidates for corrective actions C_a are considered as decision variables in the model (degrees of freedom when searching for the cheapest solution within the secure operating area). The objective of the optimisation routine is to minimise the overall costs of deploying corrective actions:

$$\min \sum_{r \epsilon C_a} \lambda_r^a a_r + \sum_{g \epsilon G} \lambda_g^{fcr} \Delta P_g^{fcr}$$

The overall costs of deploying the corrective actions can be divided into direct costs i.e. costs of the corrective actions and indirect costs i.e. costs related to the effects of corrective actions and reaction of other power system components to them. In the equation above, direct costs are given as $\sum_{r \epsilon C_a} \lambda_r^a a_r$ where λ_r^a is per unit cost of corrective action and a_r is extent of the corrective action. As an example of indirect costs, costs of deploying FCR reserves are taken into account $\sum_{g\epsilon G} \lambda_g^{fcr} \Delta P_g^{fcr}$ where G is a set of generators that participate in FCR service to the system, λ_g^{fcr} per unit price of FCR for generator g and ΔP_g^{fcr} total deployed FCR per generator g.

The optimisation model has been implemented in *Python Pyomo*. The solution of the optimisation model gives a set of corrective actions with their extents that returns post-contingency operation of the system in a secure area at minimum total system cost (as defined in the equation above). Such calculated corrective actions are further communicated back to the NEWEPS Test & Demonstration platform as output from the optimal corrective actions app.

5.3 Integration within the NEWEPS Test & Demonstration platform

In the environment established by the NEWEPS Test & Demonstration platform, the application combines the model data and the streamed PMU measurements (according to the C37.118 standard), in order to propose updated corrective actions that are relevant to the current operating point of the system. The modifications of the WAMS platform to accommodate the WAMPAC functionality includes:

- real-time N-1 contingency analysis tool
- visualisation of information on post-contingency states of the system and proposed corrective actions for securing the system operation
- control system for applying of the tailored corrective actions after the occurrence of the specific contingency.

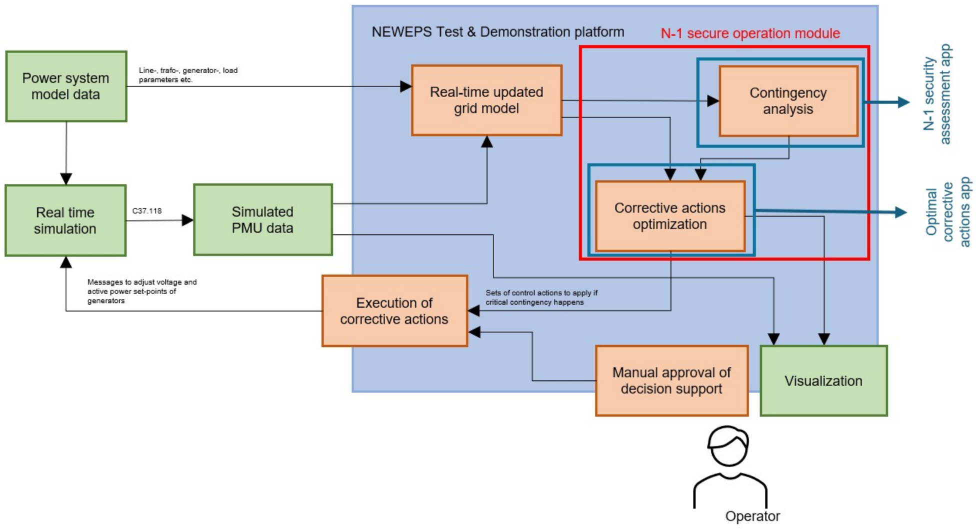

Figure 105: Integration of WAMPAC solution within the NEWEPS Test & Demonstration platform

A block diagram of the integration of the WAMPAC solution within the NEWEPS demonstration platform is given in Figure 105. It should be noted that the block diagram emphasises the required information flow, which is not necessarily accurate in terms of implementation. From the diagram, it can be seen that the N-1 secure operation module (marked with a red square in the figure) is interfaced with three blocks:

- **Real-time updated grid model**: This block reads the power system model data, and updates fields according to the most recent PMU data frames, including e.g., active and reactive power load, as well as line outages, etc.
- **Execution of corrective actions**: Applies the corrective actions proposed by the N-1 secure operation module on the request of the user. In the implemented solution, this involves updating active power and terminal voltage set-points of generators in the real-time simulation.
- **Visualisation**: This block visualises information on the critical contingencies and corresponding post-contingency states of the system together with proposed corrective actions to secure the system operation in these states. The visualisation block is the main block for communicating the outputs of real-time simulation and outputs of the N-1 secure operation module.

5.4 Validation

Information from the WAMPAC solution is presented in the graphical interface of the NEWEPS Test & Development platform as shown in Figure 106.

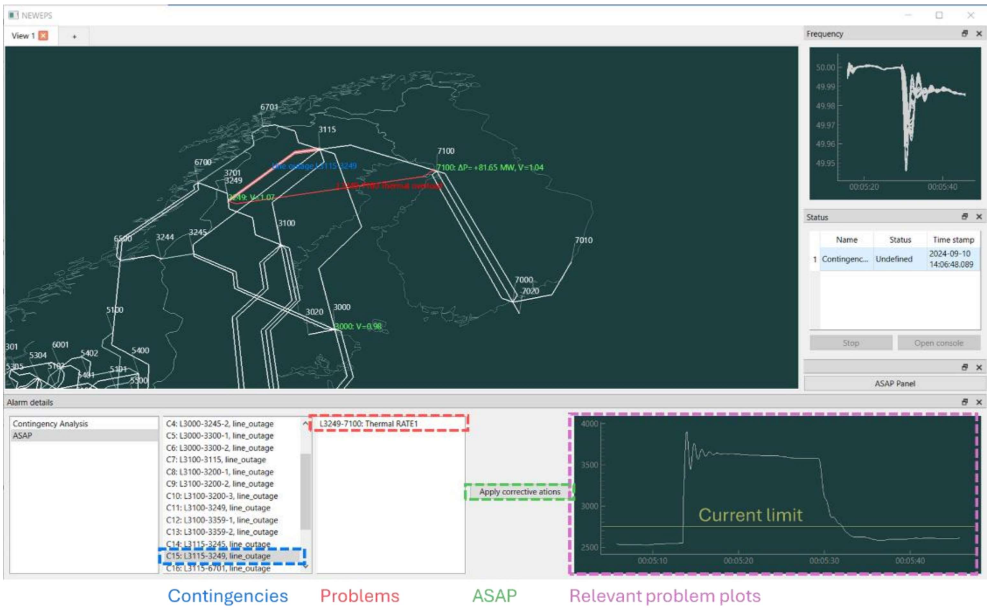

Figure 106: The GUI for showing results and controls for applying corrective actions from the WAMPAC N-1 secure operation module.

Several test cases were carried out to test the integration of the WAMPAC solution, one of which is described in the following.

A contingency in form of a line trip between bus 3115 and bus 3249 is included in the contingency list, called C15 in the GUI highlighted in Figure 106 with a dashed blue rectangle. The element affected by the contingency are indicated in blue on the single line diagram of Figure 106.

In case of contingency C15 occurring, the system identifies that the loading limit of line 3249-7100 will be violated. This is indicated by colouring the violated limit in red in the single line diagram. All the violated operating limits are besides being indicated on single line diagram also listed in the panel at the bottom of the screen (dashed red rectangle in Figure 106.

The system automatically calculates and proposes the corrective actions which are shown in single line diagram, aggregated to bus level in green text. In this specific case the optimal remedial actions would be to:

- adjust the voltage set-points of the generators connected to bus 7100, 3000 and 3249 to 1.04 pu, 0.98 pu and 1.07 pu respectively, and

- increase the total active power production from the generators connected to bus 7100 with 82 MW. (Corresponding decrease is covered by the generators participating in the FCR response.)

When selecting one of the identified critical contingencies from the list, a corresponding real-time plot of the affected quantity with its limit (in this case current on the line 3249-7100) are shown in the bottom right corner (see Figure 106). Analysing the real-time plot, we can see that when the first event happens (disconnection of the line 3115-3249) the loading of the line 3249-7100 goes above its limit. By applying the suggested corrective actions, the line loading returns below its limit. The corrective actions are applied by manually pressing the button "apply corrective actions" indicated with dashed green rectangle in Figure 106. In the implementation of the WAMPAC solution, the corrective actions are calculated to keep at least 5% margin from the operating limits.

5.5 Summary

The presented WAMPAC solution enables secure post-contingency states by deploying an optimised set of corrective actions. The solution is based on the use of optimisation methods and relies on the mathematical model of the system. The WAMPAC solution is implemented to work in real-time and has been integrated as an application in NEWEPS Test & Demonstration platform. Based on the input information (system model, operating point, and contingency list), the presented WAMPAC solution calculates and provides the following information to the operator:

- List of critical contingencies with information on jeopardised system post-contingency operating limits.
- List of corrective actions tailored to each critical contingency to secure the system in post-critical contingencies states.

An implementation of the WAMPAC solution could include automatic deployment of the corrective actions, or it could be implemented as an open-loop solution with actions being manually deployed by the operator.

The presented solution has been tested in a real-time environment and validated through three distinctive case studies. In all three case studies, the algorithm managed to detect post-contingency problems and propose the corrective actions in real-time. To validate results of the algorithm, the identified "critical" contingencies have been applied to the system after which the recommended corrective actions were deployed. After applying the contingencies, the system was indeed in a non-secure operating region with multiple violations of the operating limits. With deployment of suggested corrective actions, the system operation returned within secure region.

The example of a WAMPAC solution presented in this chapter shows, above all, the feasibility of using optimisation-based methods in real-time and how powerful these methods are in addressing complex system problems. The calculation of the corrective actions is done with strict mathematical guarantees meaning that the main source of imprecisions might arise from uncertainties in the system model. However, the problem of eliminating system model uncertainties is addressed in the NEWEPS project by utilisation of PMUs with WAMS and estimation techniques. The presented WAMPAC solution has a modular and easily upgradable structure making it easy to adapt to different platforms and specific needs of the operator.

6 Conclusions and future outlook

6.1 Key achievements

The main goal of the NEWEPS project has been to develop and demonstrate technical methods for monitoring and controlling the Nordic power system to pave the way for a system with 100% renewable energy.

The key achievements of this work include:

- Assessment of pros and cons of different architectural designs for WAMS & WAMPAC solutions, and the values of integrated utilisation of PMU data in operational tools and procedures.
- Importance of data quality and solutions to improve the quality and reliability of data in a WAMS & WAMPAC environment.
- Evaluation of effective visualisation solutions and easily navigable information structures to enable the operator to achieve an increased situational awareness.
- Development of WAMS methods to improve the monitoring of power system dynamics, specifically regarding voltage stability and low frequency oscillations. Here, the evaluated and further developed indicators provide strengthened abilities to: assess the distances to voltage instability, track how the damping of inter-area mode develop in time, and distinguish forced from natural oscillations.
- Development of WAMPAC solution, where optimal corrective actions are proposed to mitigate impact of critical contingencies.
- Development of a standards-based test & demonstration platform, based on the learnings from architectural, data handling, and visualisation perspectives, which has enabled the prototyping, testing, validation, and successful demonstration of the WAMS and WAMPAC applications developed within the project.

Some of the main results from the NEWEPS project are described in this report, and additional results and further details can be found in the following publications:

[1] A. ter Vehn and L. Nordström, *Dynamic state estimation considering topology and observability in multi-area systems*, IEEE PES ISGT EUROPE, Grenoble, 2023

[2] A. ter Vehn and L. Nordström, *Estimating unobservable machines in multi-area power systems considering model imperfections,* IEEE PowerTech, Belgrade, 2023

[3] A. ter Vehn, L. Nordström and S. Apelfröjd, *Performance Evaluation of Hybrid State Estimation Using Real TSO Data Sources*, IEEE PMAPS, New Zealand, 2024

[4] A. Zeno, K. O. Uhlen, *Improvement of System Identification using N4SID and DBSCAN Clustering for Monitoring of Electromechanical Oscillations,* IEEE PowerTech, Belgrade, 2023

[5] D. Bergman, R. Eriksson and M. G. Alavijh, *Evaluation of Forced Oscillation Detection Methods*, IEEE PES ISGT Middle East, United Arab Emirates, 2023

[6] D. Bergman, R. Eriksson and M. Ghandhari, *Initial Results in Distinguishing Between Forced and Natural Oscillations Using PMU Data*, SGSMA, USA, 2024

[7] E. Hillberg, et al., *Standards-based interoperable testbed for development and assessment of stability monitoring applications in the Nordic interconnected grid*, CIGRE, Paris, 2024

[8] H. Haugdal, S. d'Arco, K. Uhlen, *A Platform for Development and Testing of WAMPAC Applications based on Kafka Streaming*, IEEE PES ISGT, Croatia, 2024

[9] J. Björk, D. Bergman, H. Ekestam, H. Haugdal, E. Weihs, *Recursive Mode Shape Tracking in Power Systems*, submitted to IEEE Power Engineering Letters, Nov 2024

[10] K. O. Uhlen, et. al., *Wide Area Monitoring and Protection - Application Developments and IT infrastructure*, CIGRE, Paris, 2024

[11] V. M. De Souza, H. R. De Brito and K. O. Uhlen, *Comparison of Voltage Stability Indices Based on Synchronized PMU Measurements*, SEST, Türkiye, 2023

[12] V. M. De Souza, H. R. De Brito and K. O. Uhlen, *Comparative analysis of online voltage stability indices based on synchronized PMU measurements*, Sustainable Energy, Grids and Networks, Volume 40, 2024

[13] V. M. de Souza, H. R. de Brito and K. O. Uhlen, *Performance Assessment of Voltage Stability Indices for Real-Time Power Margin Estimation*, SEST, Italy, 2024

6.2 Road map for deployment and integration

The NEWEPS project has demonstrated the ability to develop a system that supports detection and analysis of criticalities of the power system dynamic behaviour. The main use cases which have been studied within the project include:

- Detection and estimation of natural and forced low-frequency oscillations.
- Calculation of voltage stability margins.
- Visualisation of power system dynamics and islanding.
- Counter measures to mitigate thermal and voltage limit violations.

The successful implementation of WAMS and WAMPAC utilizing PMU data relies on meeting several core prerequisites and maintaining stringent quality assurance. It is essential to ensure that the fundamental conditions, maintenance, calibration, improvement processes and system availability meet pre-defined standards for accuracy and reliability. To derive the anticipated benefits from WAMS, the system must be fully integrated into the organisation. This comprehensive integration involves ongoing management, use, and development, which will impact the organisation in terms of resource allocation, skill development, and potentially reshaping workflows.

A robust WAMS deployment benefits from close collaboration with end-users within the organisation to align and to ensure a clear process to improvement requests and maintenance needs. Many of the identified processes are interconnected and necessary for overall system success. Use cases across the organisation may have unique requirements, necessitating different handling and close interaction with users to address the specific needs. Quality assurance and fulfilling operational requirements are critical for moving from a test system to a fully operational system. These requirements will vary depending on the intended applications, making it crucial to prioritise needs and maintain ongoing engagement with users regarding data visualisation and the information displayed. A clear link to the derived benefits is fundamental to justifying the efforts and resources invested. A thorough security and vulnerability assessment, compliant with current organisational processes, is necessary to address the increased exposure associated with the integration of WAMS and WAMPAC. Building organisational support and developing competencies related to WAMS and WAMPAC is also of high importance. As new applications are developed and integrated, specific user training should be planned, with sufficient time allocated within the project to prepare and conduct these training sessions. After implementation, training programs for new users must be sustained to ensure ongoing competency across the organisation.

The project identifies the need for further development regarding the creation of strong decision support, to enable the operator to act with confidence at an early stage. In order to act effectively, it is of significant importance for the operator to receive a clear view of the operating situation and to get access to a list of remedial actions, together with the support to decide upon the most suitable action. There are several challenges to provide the right level of information to the operator. WAMS and WAMPAC solutions enables the operator to identify and understand the criticality of the dynamics of the power system, which today are more or less invisible. The system needs to provide guidance for the operator on how to mitigate an identified criticality, since only identification of an emerging problem without information of suitable actions does not alleviate the situation. Therefore, it is important that system development goes hand in hand with operator training and development of routines and instructions. Thus, the operator has a better understanding of the type of dynamic events that can emerge and what kind of actions that are possible to use in order to improve the system security.

Future developments of WAMS and WAMPAC solutions should be accompanied by developing action plans for dynamic events. Both the technical solution and instructions for the operators should be developed unanimously to create the most value. To make sure that the system provides the operator with the right level of information which is correct, trustworthy, and reliable it is very important that the application end users are involved during a development of a system solution. Since the time available for an operator to decide what action to take is very short, it is important that the decision support can be trusted, and its guidance is presented in an easily understandable way. For the operator to feel confident, the tool should be transparent, so the remedial actions suggested can be evaluated in relation to the operator's experience.

6.3 Steps for future development

To support the deployment of Nordic WAMS & WAMPAC solutions, several steps for future developments have been identified, including:

- Development of necessary IT infrastructures (secure communication, data storage and management of large amounts of data) for implementation of WAMPAC solutions.
- Further development of environments to support collaborative research and development, including development platforms for demonstration, testing and pilot projects.
- Advances in visualisation solutions to enable operators situational awareness.
- Further research on development and improvements of Wide Area Protection and Control solutions considering assessment of corrective and preventive remedial actions.
- Further research, development, and testing of wide-area monitoring methods.
- Advances in root cause and contingency/look-ahead analysis.

6.3.1 IT infrastructures for implementation of WAMPAC solutions

Solutions to enable secure and efficient data handling are needed for the implementation of WAMPAC. Advances in machine learning and AI for power system operational purposes are underway[86], and will be able to support the handling of the vast amount of data created and utilised in a large scale WAMPAC system. Requirements on this type of systems and solutions will differ between organisations, which may have a direct impact on the deployment on a system over-arching several countries. Decisions on architectural and other perspectives will influence IT infrastructure choices, and common development of strategies could support the WAMPAC deployment.

6.3.2 Environments to support collaborative research and development

The NEWEPS project proposes that a collaborative platform is used for future research and development of WAMS and WAMPAC solutions. A view of such platform is presented in Figure 107, illustrating how a cloud environment could be utilised for research, academia and TSOs to commonly develop, test, and validate new and innovative solutions.

[86] CIGRE Technical Brochure 946, WG C2.42, *The impact of the growing use of machine learning/artificial intelligence in the operation and control of power networks from an operational perspective*, CIGRE, 2024

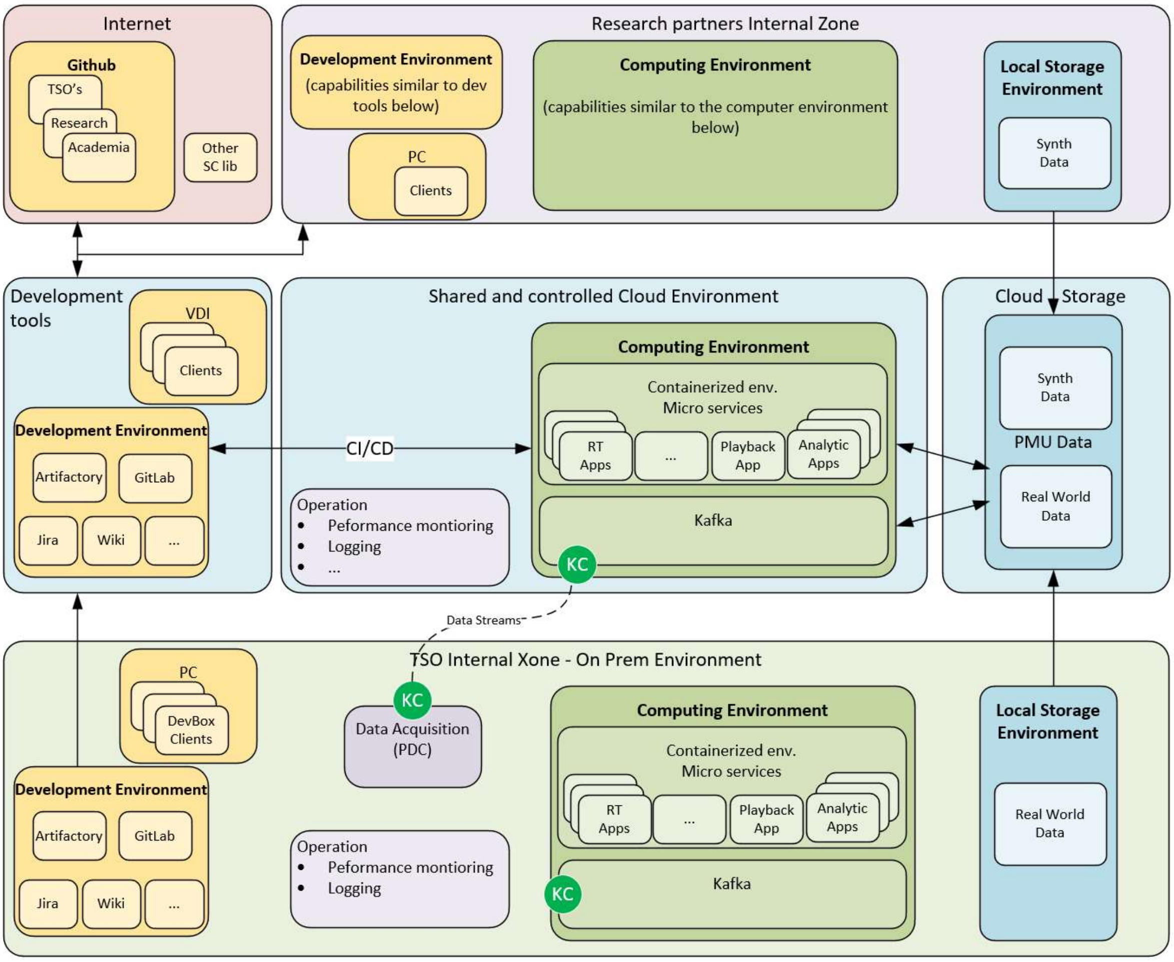

Figure 107: R&D collaboration platform.

The objective for an R&D collaboration platform is to ensure practical collaboration with "stretched" development teams located in different sites and domains, ensuring:

- Early access to managed test data from project start-up.
- Curated data sets for unit testing and test data with noise/artifacts, from both real-world power system process and from power system simulation.
- Modern development techniques, iterative development and testing principles.
- Common principles for runtime and integration architecture from project start to end.
- Recurrent demonstration for user reference groups.
- Preservation of project results, as source and binary code, configuration data and test data.

The following principles are proposed for the collaboration platform:

- A cloud-based platform, taking advantage of attribute-based access control.
- Remote development clients and/or Virtual Desktops.
- Integration of partners source code libraries.
- Coding standards and best practices.
- Orchestration, Deployment Pipelines, Continuous Integration/Continuous Deployment.
- Automated testing.
- Scalable runtime environment.
- Containerised computing environment.

- Staging (multiple environment).
- Integration environment with streaming capabilities.
- Virtualised platform for 3rd party products and support.
- High performance Data Base.
- Optimised for time series data.
- Operational logging and Performance monitoring.

6.3.3 Visualisation perspectives to enable situational awareness

As part of the continued development of the concept and interaction model, it is recommended to investigate the following aspects:

1. **Information layers and a more detailed 3D Model.** This involves implementing a 3D visualisation that provides more detailed insights into the physical grid infrastructure, enabling operators to zoom in on different facilities and access their data. Additionally, it includes the option to activate more types of information layers relevant to operators for monitoring and controlling different phenomena within the grid.
2. **Integrated data systems** would involve the development of a single platform that consolidates data from multiple systems. This platform, for instance, could provide a central dashboard where all relevant data is accessible in one place. Such an integration may streamline workflows and reduce the existing complexity of managing multiple data sources. Data security aspects are an integrated part of assessment of such system.
3. **Efficient navigation and user interface design** is about designing a user interface that would minimise the number of manual actions required to access critical information. For example, this could be a system that automatically guides the users to the required function, a location in the grid that requires action, or activates specific information layers. Integration of voice command functionality may further improve navigation efficiency.
4. **Contextual information display** would involve the possibility to customise displayed information based on user roles. This role-based customisation ensures that each user has quick access to the information most relevant to their role and tasks, without being overwhelmed by unnecessary details. For example, technical personnel should see technical data relevant to their tasks, while control room operators should see operational data.
5. **Mixed reality implementation** would focus on incorporating augmented reality (AR) and virtual reality (VR) technologies to create an immersive environment where operators can interact with the 3D model of the power grid. The benefits with a mixed reality implementation need to be investigated, but it may improve training, troubleshooting, and planning by providing a realistic and interactive representation of the grid and its infrastructure.
6. **Advanced timeline functionality** could include possibility to see both historical data and future simulations. This would allow operators not only to review and analyse past events, but also to predict future scenarios based on dynamic forecasted changes in production and demand. Real-time simulation of future situations would help to anticipate issues and make informed proactive decisions. Additionally, real-time tracking of deviations from planned changes would allow immediate corrective actions.
7. **Exploring AI integration and interaction design.** In this work, a concept was developed for interaction between humans and emerging data analysis systems, such as AI. Future research should focus on how AI models can be applied in real-world scenarios and trained using actual operational data. This would lead to a better understanding of its development potential, offer insights into how AI

can be integrated, and inform how the interaction design should be adapted to the strengths and limitations of AI systems.

6.3.4 WAMPAC considering assessment of corrective and preventive remedial actions

The presented WAMPAC solution uses an optimisation-based approach to find *corrective*, post-contingency actions that can move-back the operating point of the system into the secure operating region. A challenge that had to be addressed was that the calculations had to be run in or close to the real-time. The execution speed of the algorithm, and its ability to run in real-time, is mostly influenced by two factors:

- Complexity of the optimisation model (including mathematical modelling of all system components);
- Efficiency of the algorithm's implementation including computational efficiency of the used optimisation solver.

The mathematical modelling of the system has to be detailed enough to capture all the phenomena of interest. Adding more details in modelling above what is needed would not improve the precision significantly of the calculated *corrective actions* but might degrade computational performance of the algorithm. To address this challenge, the optimisation model used in proposed solution takes into account steady-state conditions and static stability indicators of the system. For illustrative purposes, an example of the SZI has been implemented in the optimisation model. Future work should take into account other stability criteria or dynamics constraints such as:

- Small-signal stability constraints;
- Frequency stability constraints;
- Converter-driven instabilities constraints.

The structure of the optimisation model used in the proposed WAMPAC solution allows relatively easy integration of these additional constraints. Apart from adding additional stability criteria that the *corrective actions* should address, the improvements in modelling of the problem can be done by including more system detail connected to:

- Technical constraints describing other special controllers and protection devices – an example of this would be inclusion of existing System Integrity Protection Schemes and their co-optimisation with proposed *corrective actions*;
- Nontechnical constraints – constraints that relate to the preferences of the system operator when it comes to the operation of the system e.g. maximum number of elements involved in *corrective actions*, adjustment of costs of *corrective actions*, maximum available volumes etc.

Another important consideration in the setup of the problem is that the currently proposed solution calculates *corrective actions* i.e. actions that are executed after the contingency happens to "correct" the post-contingency state of the system and return the operating point within a secure region. An alternative option to secure the system would be to change the operating point of the system before any contingency happens i.e. redispatch the system by applying *preventive actions*. The future work should consider the trade-off between applying *preventive* and *corrective actions*. The algorithm's optimisation model should also be extended to take into account *preventive actions* when finding the cheapest and the most effective overall system solution.

As previously mentioned, more details in the optimisation models might decrease the applicability of the solution in the real-time environment. So, more detailed modelling of the system should be followed with careful mathematical description of these models that can be exploited by mathematical integration methods and solvers to increase computational performance. An example to be investigated in the future is suitability of the developed optimisation model to be decomposed and parallelised on multiple processes. In the current implementation, parallelisation has been done but the questions arise how this should be done when other model features are added e.g. addition of *preventive actions* in the model.

Besides parallelisation and distributed computing, there are also other approaches to increase computational performance of the algorithm. A common thing in every software development is that the computationally demanding parts of the code are precompiled using some of the computationally efficient programming languages e.g. C/C++. Many of the Python libraries are precompiled in this way. A similar approach can be done with computationally heavy parts of the code within this algorithm. Ultimately, the whole algorithm should be translated from the prototyping, interpreter-based language like Python into languages that compile the code before their execution.

6.3.5 Wide-area monitoring methods

Direct visual inspection of measurement channels and automated alarms based on fast Fourier transform oscillations are useful applications for WAMS. These offers great value to the operator while not require much development effort, apart from building and maintaining a PMU and WAMS infrastructure. More advanced methods, such as system identification and modal analysis requires more effort to make the result reliable and accessible for operators.

The result of the system identification (e.g., N4SID, covariance driven SSI, ARMAX) depends on the quality of PMU data, but also on the chosen algorithm and its tuning parameters. For the results to be viable for the operator it is important to address quality and robustness of the implemented system identification algorithms. System identification methods are also quite computationally demanding. Improving efficiency using parallelisation should be explored. Another means to improve efficiency of real time system identification is to run the identification on a subset of available PMUs, having the option to deep dive into higher resolution system identification if requested.

The results of the system identification method can be interpreted and presented in many different ways. Oscillation frequencies, damping ratios and mode shapes are useful status indicators to present to the operator. Consistency in modes over time can serve as a mean to evaluate the quality of the implemented system identification method. To facilitate this, an automated recursive modal tracking method was developed based on the identified mode shape. A topic for further research is to investigate how such modal tracking methods can be used to evaluate the quality of the system identification, so that the operator can be more confident in how to interpret the presented information.

6.3.6 Root cause and contingency/look-ahead analysis

Evaluating the root cause of a disturbance is essential for determining an effective and appropriate response. Methods to distinguish between forced and natural oscillations were investigated in this project. This distinction is important to make since the disturbance will require different actions from the operator. Once the operator is alerted that a prioritised disturbance has occurred, the application should also suggest a course of action to improve the situation based on the identified root cause. A natural extension of the post contingency root cause analysis method is a more proactive contingency/look-ahead analysis. Such a proactive contingency analysis could perform dynamic stability assessment on a regularly updated grid model to check if the system is N-1 stable with respect to oscillations, and if not, propose a preventive action for the control room operator. The are many challenges associated with populating a representative grid model of the current situation retrieved from the estimator with dynamic models, which is underlined as one possible future work for WAMPAC solutions as mentioned in 6.3.4.

A straight-forward way to present a suggested course of action is to document previous actions taken by the operator. Perhaps this, or similar events have occurred in the past. If so, then what where the actions taken and is it a good idea to take similar actions this time? Leveraging historic knowledge of the operators lets the system account for situations and circumstances that may be impossible to foresee and model. A data base that can connect operator documentation with system events and present relevant information is needed. With a sufficient level of historic information, machine learning algorithms and other mathematical techniques can be utilised to support the identification of relevant situations and selection of suitable relevant preventive or corrective actions.

6.4 Concluding general remarks

The green shift is ongoing and large-scale energy system analysis show that it is possible to realise the transition and transform energy production to become almost 100% renewable. In most energy system analyses, there is little focus on how the systems are to be operated and managed in order to maintain secure operation of the power system.

The NEWEPS project has contributed with research and development of solutions for wide area monitoring, decision support and coordinated control. A remaining challenge is how to put it all together and one important aspect is about implementation and validation another is how to fit the new solutions into practice. This is not just about technological development. For the control room operators, it is just as much about skills and training to use the new technologies and tools that become available. We need to accelerate prototype, testing, implementation and training. Although the control room operators have not yet experienced the large changes in their daily routines, there is no reason to delay training to meet the challenges ahead.

As a critical infrastructure, security of supply will remain just as important (if not more important) for future power systems. There is a need for more advanced control systems, and secure operation depend on skilled operators with situational awareness to be able to make quick and correct interventions in critical situations. At the same time, we must remember that dependence on increasingly advanced information systems poses a risk by itself. In our uncertain world, there is a need to always be ready to face the threats of constant cyber-attacks, as well as the risk of hostile attacks on the physical infrastructure.

Solving the operational challenges through the green transition is about management, information and control systems. Through research and development, it will always be possible to find stable and secure solutions to handle identified challenges. For deployment, details are of outmost importance, and there is a need to intensify the work to get all details in place to enable the implementation of a Nordic WAMS & WAMPAC system.

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