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Wide Area Synchronization Functionality

Master's Thesis in Sustainable Electric Power Engineering and Electromobility

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Abstract

Large interconnected power systems are constantly exposed to unpredictable disturbances that may often lead to system splits. This creates two or more synchronous areas where some end up with generation surplus and the others with generation deficit, and corresponding frequency deviations, which in most cases results in load shedding. Afterwards when the subsystems stabilize, the tricky part comes when its time for resynchronization since the systems are large compared to a small area. This thesis presents a development and testing of a phasor measurement unit (PMU)-based method with the aid of Wide Area Measurement Systems (WAMS) which introduces an immediate solution for the issue of stabilization and synchronization of subsystems. PMU sensors are fast, real time-stamped accurate devices linked to the Global Positioning System (GPS) that measure synchrophasors at various points on the grid, which would help transmission system operators (TSOs) to react and counteract any event or disturbance that might threaten the system. The research employs PSS/E software to perform static and dynamic load flow analysis on the Nordic power system when a disturbance occurred in the system that led into splitting to two synchronous areas. During the resynchronization process, two methods were evaluated: the conventional method (sequential reconnection) characterized by limited data gathering and communication delays between TSOs, and the developed method (simultaneous reconnection) that leverages the use of PMUs for reconnection of the lines, hence the system's response was observed. Synchronization data that include frequency, voltage and phase angle differences from the subsystems, which were output, analyzed and compared for both methods. The results demonstrate that the simultaneous reconnection utilizing PMU sensors which provided real-time data that enabled TSOs to identify the lines that were tripped due to the disturbance created hence discovering the disturbance location and mitigate around the area of the split, as rapid as possible. In addition, the system downtime and the risk of further instability is reduced. This method added more to the understanding of the sequential reconnection method which is currently used for the resynchronization of subsystems while showcasing the benefits the simultaneous method when it comes to reconnection. Most likely in the near future the simultaneous method will replace the sequential reconnection method when more renewable energy sources are integrated.

Keywords: interconnected power systems, WAMS, PMUs, sequential resynchroinzation, simultaneous resynchronization, communication delays.

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Abdin Mohamed, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AGC	Automatic Generation Control
API	Application Programming Interface
EMS	Energy Management Systems
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible Alternating Currents Transmission Systems
FCR	Frequency Containment Reserve
GENROU	Round Rotor generator Model
GENSAL	Salient Pole Generator Model
HYGOV	Hydro Turbine Governor Model
IEEET2	IEEE type 2 Excitation System
IEESGO	IEEE Standard turbine Governor Model
IOT	Internet Of Things
KV	Kilo-Volts
MW	Mega-Watts
N44	Nordic 44 model
PDC	Phasor Data Concentrators
PLL	Phase-Locked Loop system
PMU	Phasor Measurement Unit
PSS/E	Power System Simulator for Engineering
RES	Renewable Energy Systems/Sources
SCADA	Supervisory Control and Data Acquisition system
SCRX	Bus Fed or Solid Fed Static Exciter
SEXS	Simplified Excitation System Model
SPD Group	System Protection and Dynamics Group
STAB1	Speed Sensitive Stabilizing Model
UCTE	Union for the Coordination of Transmission of Electricity
UFLS	Under Frequency load Shedding
UVLS	Under Voltage Load Shedding
WAMS	Wide Area Measurement Systems
WAMPAC	Wide Area Monitoring, Protection and Control Systems

Contents

List of Figures

List of Tables

1
Introduction

This chapter provides a brief overview of the project, its relevance and interesting aspects. In addition, it will also provide an accompanying project aim, describing the goals and achievements of the project work for this report. Furthermore, the project scope discusses the report main focus and its limitations. Finally, a project layout section outlines the subsequent chapters present in the thesis along with brief descriptions of their content.

1.1 Background

Electric power systems are considered the backbone of the economy of a nation, which plays a vital role in providing the day-to-day basic amenities of any other sector[5]. These power systems are complex interconnected networks which are composed of four important parts: generation, transmission, distribution and loads. Nowadays, with the movement towards smart grid concepts which facilitate the increased integration of renewable energies, driven by environmental concerns and energy security considerations. The power system stability, control, protection and security are compromised by these based renewable energy sources such as wind turbines and photovoltaic panels, in which are considered intermittent. This causes a reduction in the total system inertia jeopardizing the power system stability and security. Additionally, the power system exhibits power imbalances causing frequency fluctuations that pose further threats[8]. System splits are a result of this which is especially frequent in larger power systems such as Continental Europe, where the interconnected system is split into two or more synchronous areas. Some of the subsystems end up with generation surplus and others with generation deficit, and corresponding frequency deviations which often results in load shedding. After stabilization of the subsystems, the objective is to resynchronize these systems as soon as possible, in which could be tricky since the systems are large compared to a single interconnector capacity, and one interconnector is closed at a time.

Wide Area Measurement Systems (WAMS) introduces the concept of observability and its computational algorithms on a large scale for a power grid based on synchrophasors, for example Phasor measurement units (PMUs)[10, 11]. WAMS does not only tackles immediate reliability concerns imposed on a power grid but also conveys the ability to conduct real-time dynamic analysis through identification and calculation of the security margins which helps for early detection and monitoring of the system, predicting emergency and initiate mitigative actions for the system's stability[13]. Phasor Measurement Units (PMUs) being an essential component of WAMS, it helps with addressing the issue of stabilization and resynchronization of these subsystems in a simultaneous well-mannered and efficient way. PMUs are considered fast time-stamped accurate devices that measure synchrophasors which represent both the magnitude and phase angle of the electrical sinusoids at various points in an electric power grid. These sensors provide highly accurate and synchronized time-stamped[12] measurements of these quantities, and applications based on PMUs which can improve system reliability, stability and efficiency in case exposed to disturbances that may affect the entire grid. Causing the grid to split into multiple subsystems creating fluctuations in the frequency and voltage that lead to voltage instability and inter-area oscillations between these subsystems. PMUs play a crucial role in enhancing the monitoring, control, and protection of the power system.

1.2 Aim

The main aim of this project, through PSS/E simulations with the Nordic grid model, is to study different subsystems in the model and monitor electrical quantities from various points for synchronization information i.e. frequency, voltage, and angle. This information will help to develop and test a PMU-based method to simultaneously give closing orders to several interconnecting breakers that synchronizes two large subsystems. Moreover, a comparison will be made between conventional sequential reconnection of the interconnecting lines and assessing the success likelihood of the new PMU method. As a result, a faster way to stabilize and resynchronize the system can be made and used in case of a disturbance in the power grid.

1.3 Scope

The focus of this project is to develop and test a PMU-based method while utilizing PSS/E software in performing simulations on the Nordic grid model to simultaneously give connection orders for the synchronization two or more subsystems. To achieve the objectives of the project, several key tasks will be undertaken. Initially, a comprehensive literature review will be conducted to explore phasor measurements, PMUs, and power system splits. This will provide a solid foundation for understanding the Nordic grid model and its functionalities using PSS/E software. Additionally, the principles of traditional synchronization processes will be studied, alongside an examination of PMU functionality across the grid. Subsequently, subsystems will be generated from the Nordic grid model at different locations, with disturbances introduced along the grid to facilitate studies. Various PMUs will be deployed at these locations to extract synchronization information data. Analysis of this data will enable the formulation of simultaneous resynchronization orders for reconnection. Furthermore, efforts will be made to identify patterns for simultaneous reconnection in the event of disturbances. Ultimately, a PMU-based method will be developed and rigorously tested to facilitate simultaneous connection orders.

As the pace of the work throughout the process of the project will run smoothly and will effectively addresses the outlined objectives, one certain limitation will be faced that may or may not affect the output of the project. As a result, will be excluded and can be examined in future studies. Since the data collected are made through the PSSE simulations under the assumption that PMUs are used to collect the data because PMUs are not readily available and at use, therefore some of the data maybe subjected to some slight errors.

1.4 Project Layout

This chapter served as an introduction for the project as well as giving a clear aim behind conducting this master thesis and in which it was achieved. The next chapter will provide a literature review about the main topics that will be discussed and mentioned in the project and the reasoning and importance for including this information for acquiring a comprehensive understanding. This is followed by chapter three where the methodology for simulations of the model were made for the creation and study of the subsystems, in addition to their responses to certain conditions. The consequent chapters will be discuss the results of the simulations and will propose the PMU-based method that was developed and tested. A conclusion of the work and future recommendations will be provided in the closing chapters. Additionally, a comprehensive list of references cited in the thesis will be provided and an appendix presenting all the supplementary materials that were used in the report.

2
Literature Review

This chapter will present relevant information about the main topics which will be encountered during the process of the project. Each topic will be discussed in sections which will aim to provide a thorough understanding of the theoretical foundations and methodologies that inform the research conducted in this thesis.

2.1 WAMS

Through the years advancements in power systems protection and monitoring have led to the emergence of Wide Area Measurement Systems (WAMS). It plays an important role in the observability, stability and overall operation of modern power grids. WAMS is an advanced measurement technology used to improve situational awareness and visibility within power systems of today and future grids. It consists of sophisticated information tools, operational infrastructure which helps in collecting data for the operation of complex networks. It provides overall monitoring, control and protection of the power system[5].

The system is designed to address problems related to the security and reliability of power networks, aiming to detect and monitor system security and deploy wide area information, control schemes and actions. For the power network to be operated securely and safely, different information should be extracted from different locations of the network, then collected in a database in which necessary decisions should be made based on the status of the power network. Therefore, WAMS applications rely heavily on the communication network for the collection of data and decision making for localized actuators [10]. A telecommunication system with certain specifications is necessary.

The following specifications of a telecommunication system were needed for the WAMS to function properly [7]:

- High Bandwidth: it must have the ability to send and receive alot of information like bus voltages, current and power of lines, etc..
- Rapid Transfer of Information: Faster communication system means faster sending and receiving of signals, hence information will be obtained with minimum delay.

WAMS usage ensures the permanent monitoring of the dynamic behaviour of the power system. Figure 2.1 below depicts the architecture of the wide area measurement system[15]. The main components consist of: PMUs, PDCs, communication networks, data storage and application software. The number of substation PDCs are dictated by how large the power system and its requirements. PMUs placed at substations measure the voltage, current and frequency which in turn sent to a substation PDC then to the central PDC [15].

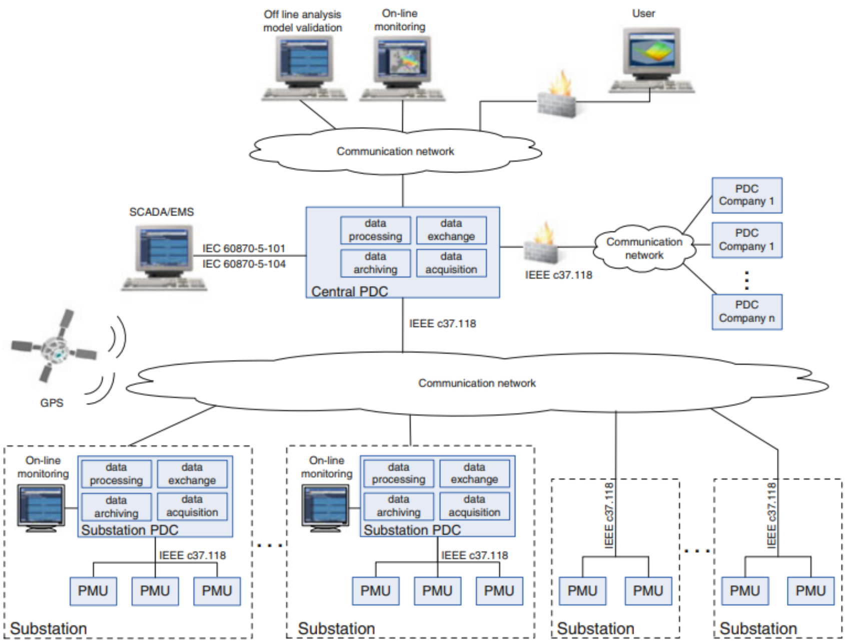

Figure 2.1: Generic Architecture of the WAMS[15] ©2014 Tadeja Babnik, Kay Görner, Bojan Mahkovec. Permission obtained for reuse, courtesy of Springer Nature and Copyright Clearance Center

The substation PDC which is considered to have an important role in the WAMS, where it has different applications which are mentioned below:

- acquires data from PMUs
- data time synchronization
- evaluates received data
- sends data to central PDC
- exchanges data with the local SCADA
- archives data locally and performs local data analysis and protection actions.

2.1.1 WAMS functions based on Power Grid Application

Conventional SCADA systems cannot analyze system dynamics and are only limited to measure modes of the power system in steady state. On the contrary, WAMS allow for constant monitoring of the system operation during the dynamic mode. It provides a time synchronized data acquisition every 20 ms(for a 50Hz system) with millisecond precision [16]. Structuring fundamentals for configuration of WAMS on a real power grid are mentioned below.

2.1.1.1 Communications

Wide Range communication protocols of the system are provided for collection and receiving of synchronized phasor data. For example, according to the IEEE protocols, the PDC supports the PMU communication rules given by conventional IEEE c37.118 [31] and IEEE 1344 communication protocols. This allows for at least 100 PMUs with a full resolution of 50 samples per second for 50 Hz power systems, to provide data to the PDC responsible. Where as a server, the PDC can connect with other PDCs for exchanging real-time data required with other companies, such as transmission network system operators [15]. In addition, the possibility of simultaneously sending of data at the same frame rate speed to different clients and filtering the data upon what was requested by the client. Furthermore, using standard protocols provided, the PDC can communicate with other systems to send and receive commands from conventional SCADA/EMS systems.

2.1.1.2 Data Analysis

This crucial stage includes complex real-time calculations required for the electrical power system operation[32].

- Monitoring of the power transmission over specific transmission lines by calculation of the voltage stability
- Frequency stability calculations which allows detection of frequency changes that occur from sudden load loss or power shortages
- Power fluctuation functionality that identifies power fluctuation on lines by calculating the fluctuation frequency,its amplitude and damping factor
- Monitoring of phase angle between two substations in the grid

The difference in phase angle can increase with an increase in the system load. This shows the importance of a successful communication and information exchange between the two substations about phase angle differences[32]. Thus, monitoring of the phase angle can also include:

- Phase angle difference measurement between the two substations
- Threshold assessment for triggering alarms and warning dispatchers in case of violation

2.1.1.3 Monitoring functions

As the data received is being analyzed, the initiation of the monitoring function which takes the values in correspondence with the threshold value, checking if it is greater or smaller. This process is similar to phase angle difference monitoring function. Furthermore, if two values exceed the threshold value, the monitoring function is initiated for detection of differences between the modules that issued the values. This mitigates any exclusion of data that can cause problems during future data analyses[32].

2.1.1.4 Custom Functions

The system comprises of programmable logic tasks and employs numerous libraries of operations for diverse purposes, including arithmetic, numeric processing, logical operations, complex number arithmetic, comparisons, and more. Consequently, custom function blocks can be generated depending on the given application and the requirements given by the users. One such example of a custom block is a troubleshooting diagram[32].

2.2 SCADA

SCADA is recognized as a computer-based system for automation and control [5] which, through operational controls assisted by computers, is used for the collection and processing of data over long distances[9]. The system integrates both control and data acquisition functionalities[5]. Monitoring, Data Presentation and Acquisition, Supervisory Control and Alarm display represent the main functions of SCADA. Through these processes it is able to provide a steady, low sampling density (between 1 and 10 sec) and non-synchronous data of the power system [5, 15]. However, its slow scan rate measurements make it unsuitable for real-time tracking of power system dynamics particularly in the occurrence of the large disturbances in the system[20].

2.3 Conventional Methods of Synchronization

With the expansion of renewable energy sources and its utilization which leads to high system loading and fluctuations[36], TSOs have to ensure power quality and supply continuity amidst an interference or an event. Proper selection of synchronization algorithms are necessary for meeting the requirements for maintaining the integrity of a power system[35]. A way of addressing these challenges was the creation of methods for restoring and regulating the power system during the occurrence of an event[35]. To furthermore manage disturbances and facilitate the synchronization of large interconnected power systems, these methods were often used in combination. Some of these methods are discussed below.

2.3.1 Emergency Control Schemes

Emergent status within large power systems can arise from cascading line failures, generation unit outages, and other factors. Such occurrences invariably brings substantial power imbalances, wherein automated support mechanisms prove inadequate to swiftly provide for the power deficiencies. Consequently, operators resort to manual interventions, although often with limited success, to address the rapid post-disturbance phenomena. This, in turn, leads to deviations of frequency, voltage, and power flow to leave their secure operational parameters of the system [43, 44]. Moreover, extra risk to the system thus increasing the chance of blackouts throughout the power system.

This prompted the planners and operators of the power system to devise automated, dependable systems capable of managing potential contingencies [45]. Here, Emergency control schemes come to play, which are implemented promptly and automatically in emergency situations to ensure system stability and facilitate resynchronization of split power systems. These schemes may involve measures such as load shedding, generation re-dispatch, transformer tap adjustments, DC power modulation, and reactive power control, all aimed at stabilizing the system and providing support for resynchronization attempts[43].

Moreover, with advancements in measurement and communication technology of WAMS, the utilization of FACTS devices is increasingly preferred for their effectiveness when it comes to disturbance control. Additionally, emerging concepts such as fuzzy logic and neural networks offer enhanced capabilities in emergency detection and control[45]. This augmentation empowers system operators to optimize power network utilization, consequently fortifying its resilience against significant disruptions [45]. To get a clearer idea, some of these automatic schemes are described below. Moreover, to highlight that these schemes can be used together as a way to prevent an event that struck the power system.

2.3.2 AGC

Power production and load demands are constrained by the operation of the power system, which must maintain constant equilibrium. As specified by the grid codes, the frequency of the network is kept within defined limits to uphold this equilibrium [40]. Two control loops are responsible for this task, namely primary and secondary. The primary control loop prevents sudden frequency variations before triggering frequency protection switches by the intervention of the governor droops, which may introduce steady-state errors. Meanwhile, the secondary control loop, known as AGC or load frequency control (LFC), is implemented to adjust the system frequency to its nominal value within the power system network[40].
AGC objectives mainly include[40]:

1. Ensuring the steady-state system frequency aligns with its nominal value.
2. Keeping tie-line power flow close to its scheduled value.
3. Managing overshoot and settling time within acceptable ranges.

AGC plays a pivotal role in ensuring the smooth and efficient operation of any power system . Its primary goal is to maintain the operating frequency within prescribed limits and uphold the intended power interchange levels[40]. AGC operates in real-time, employing a fast-acting distributed proportional-integral-derivative (PID) control form which responds to demand disturbances by adjusting the generation levels of different subsystems resulting in regulated local frequency deviations while also preserving scheduled tie-line flows[39].

As modern power infrastructure undergoes significant transformations due to the integration of large-scale renewable energy sources, the emergence of concepts like microgrids, smart grids, deregulation phenomena, and the digitalization of power system control structures pose challenges to AGC strategies[40]. Particularly, with the increasing presence of geographically distributed wind generation plants makes traditional AGC approaches less feasible. This necessitates a more holistic and optimal approach to real-time AGC operation, dependent on forecast accuracy and executing the plan based upon the forecast[39]. This makes AGC not only essential for ensuring reliability, security, and economic operation but also demands an innovative and enhanced control framework that meets the evolving requirements of future power systems[40].

2.3.3 Load Shedding

Load shedding is an emergency control measure [34], that is used whenever an event or a disturbance causes the power grid to overload. It functions as a planned load management scheme, initiated based on local frequency and voltage measurements, used to balance the power consumption in the power system upon less power production[46], hence reducing the strain and impeding further degradation of the power system. Load shedding schemes are mainly divided into two types; under voltage load shedding (UVLS) and under frequency load shedding (UFLS). The frequency and voltage thresholds, decided by TSOs, after the occurrence of a disturbance determine whether which activation of load shedding schemes is necessary[34].

In the event of exceeded frequency thresholds, UFLS is advised as a way to maneuver upon this matter. Frequencies at load ends are measured locally, where the decision to shed a load is made. UFLSs used are based on static models in which the shedding of the load depends only on frequency measurements[47] to mitigate rapid reduction in frequency[34]. Although this could be a viable solution however, these schemes are fixed in spite of the magnitude of the disturbance. This could lead to issues like under-shedding and over-shedding problems which can further deteriorate the frequency stability of the power grid[47].

UVLS is recommended during circumstances that the voltage thresholds are surpassed. This occurs when the loads in the power system fails to meet the supply of reactive power needed to maintain the stability. Protective relays located at local buses equipped with fixed voltage pickup thresholds, fixed time delays and fixed amounts of loads to shed, are responsible to mitigate this event in case of its occurrence [48]. Whilst this is a feasible solution, an emerging challenge that is the coordination between TSOs and DSOs resolving which decentralized under voltage relays to trip without causing excessive load shedding that consequently causes inconvenience for large number of customers[48].

2.3.4 Manual Resynchronization

This method involves manually synchronizing the grid through coordination between system operators and control centers in case the automated procedures become invalid. While it can be time-consuming and complex, it's necessary to restore the system in a coordinated manner. The restoration and resynchronization plan is mainly executed by the TSOs[36]. During states of emergencies or whether the possibility of blackouts are immanent, these plans are activated, involving coordination among TSOs, Distribution System Operators (DSOs), and Significant Grid Users (SGUs), ensuring constant communication and information sharing to successfully execute the plan and return the system to normal operation[36]. Depending on the nature of the event, TSOs implement various strategies in accordance with other operators and users, in which are mentioned below.

2.3.4.1 Top-down & Bottom-up Re-energization strategies

These restoration strategies are implemented in the rare occurrence of a system-wide blackout, delineating the process for restoring electricity to the system[36]. The network restoration process for re-energization primarily relies on two principles[36]:

- Top-down strategy: involves the external use of voltage sources from tie lines to re-energize a separated distributed system.
- Bottom-up strategy: the readiness to resynchronize with another area by self-re-energizing parts of its own load frequency control area.

To provide further clarity on their usage, a distinction is made between these strategies[36]:

- Top-down strategy necessitates neighboring TSOs assistance to re-energize the system of a particular TSO.
- Bottom-up strategy requires that available power sources with black start capability within the area of a TSO or DSOs to self-re-energize.
- A combination of both top-down and bottom-up can be used to enhance the chances of re-energization.

2.3.4.2 Build-down, Build-up & Build-together Re-energization strategies

The ENTSOE network code conveys solely on coordinating actions and relationships between TSOs across different control areas during network restoration. However, it does not address the responsibilities of DSOs in this regard[36, 38]. To tackle this gap, three strategies were created to depict the roles of DSOs with regard to TSOs, particularly the need for black start capabilities in the event of an outage[36]. These strategies for re-energization are outlined as follows[36]:

- Build-down strategy: involves the absence of power sources with black start capabilities within the distribution network. In such cases, the upstream TSOs aid to re-energize the affected DSOs system.
- Build-together strategy: where both TSOs and DSOs have the ability to black start. Consequently, the disrupted system can be re-energized independently.
- Build-up strategy: the capability of power sources to black-start are only available within the distribution networks. Consequently, the affected DSO's system can be re-energized, while also aiding in the restoration of its TSO.

It's worth noting that there exist seven potential combinations of network restoration strategies from the above individual strategies mentioned through the coordination of TSOs and DSOs[36].

2.4 Synchrophasors

Synchronized phasor measurements, also known as synchrophasors are defined as phasor values of the magnitude and angle that are calculated from several data samples of the cosine signal of voltages and currents with the use of standard time signals as a reference to an absolute point for the measurement[21, 22]. This results in measurements across the interconnected power gird having common timing reference and hence making comparison with other readings easier. Synchrophasors introduce a new approach for improving the visualization of the power system conditions. This advancement has improved the protection and control devices across WAMS of a power system which in turn progressed the view of the observability of the power system dynamics[21].

2.4.1 PMU devices

Synchrophasors are measured by an electronic device called a PMU that provide synchronized and frequency measurements for three-phase AC voltage and/or current waveforms[22]. PMUs with the aid of Global Positioning Systems (GPS) have evolved over the years for various power system applications. This development provide the accurate time stamp of synchronized data samples across the power system[23]. The time stamps linked with each measurement will assist operators in obtaining a comprehensive understanding of the power system's operation [9]. These data samples are collected with high precision from a synchronizing source with the correct timing reference which could be either produced locally (i.e. within a specific region or subsystem) or globally (i.e across an entire interconnected power grid) as required by the system operator[21]. For sending and receiving of the data samples, a transmitter can be built in the PMUs itself or installed in the substation where the synchronized readings are distributed across other PMUs or any other device that acquires it[21].

PMUs capture synchronized measurements at speeds of up to 60 times per second compared to the conventional SCADA measurements[12]. Repetitive discrete Fourier Transform (DFT) algorithm is used for processing and filtering of these measurements where for each sample a magnitude and angle is produced. Since the optimal method for continuous monitoring of the input wave forms is using a recursive form of the phasor equation[24], measurements are taken individually from all three phases and then combined to produce a positive sequence phasor where it is stored internally as tables which can also be transferred between system operators depending on their use[23]. Voltage and current magnitude and phase, real and reactive power, frequency and impedance can all be calculated using the positive sequence from the measured samples. In addition to calculation of these electrical quantities, the positive sequence can be used for the evaluation of the power system performance by constructing dynamic studies, state estimation and model verification[23, 24].

The utilization of PMUs within WAMS presents various advancements for the system operators of the power system[12]. These advancements can be grouped into three categories, as follows:

1. Improving system analysis and planning (i.e. event analysis, verification of model for stability)
2. Applications for reinforcing real-time grid operations while increasing situational awareness
3. Applications for response-based control that utilize real-time wide area information for implementing automated control actions within the power system

2.4.1.1 PMU Applications

The availability of PMUs and synchrophasor measurements have created new possibilities in wide area monitoring, protection and control of any power system. The applications created by the PMUs on WAMS can be deployed for the prevention and mitigation of different kinds of events that are exposed upon the power system. The advancements that were mentioned above portrays within it different applications. Some of these applications are presented below:

A. Oscillation Monitoring:

PMUs have given the opportunity for system operators to directly observe the system oscillations prior to a system disturbance. Through simulations, major system components of the model can be known and corrected according to the observed dynamic phenomena[24]. Local and inter-area power system oscillations are caused by power system disturbances such generation loss and line trip which conventional applications like SCADA cannot detect these kinds of oscillations due to information delay[7, 12]. The fluctuations created are a result of generators oscillating against each other in different areas. This unfamiliar operation of the generators can obstruct the power flow through some parts of the power grid, eventually causing network instability and can even lead to wide blackouts[21].

For prevention of such cases, PMU-based schemes have been developed for the detection of impending unstable operating conditions, dynamic power flow changes in both ends of the tie-lines and in turn alarming system operators[20, 21]. The PMU detects the existence of low frequency oscillations, estimation of degree of damping and enabling operators to narrow down the cause of the oscillations and the corrective measures needed to be taken[12].

B. Voltage Stability Monitoring:

Voltage stability refers to maintaining steady voltage levels at all buses of any power system from its initial operating conditions, after undergoing any type of disturbance (i.e. load fluctuations, changes in generations profile)[12, 22]. Through existing practices, it was proven that most power systems have the ability to withstand heavy voltage disturbances in the transmission systems. The continuation of the system instability is the deficit of reactive power, and arises due to the large distances between the generating units and load ends[20].

In addition to the inadequate management of these disturbances is what leads to a spread out subsequent events which results in voltage collapses because the maximum load limit has been exceeded. This affects neighbouring regions and can also impact the whole power system[30]. The data collected from PMUs located on different buses in the power system helps in computationally predicting voltage instability with respect to changing system conditions, by assessing the collapse margin in real-time for performing better control actions for avoiding cascading events that lead to power outages[12, 22].

C. Communication Availability:
High-speed communication infrastructure is an important factor for determining the occurrence of a disturbance upon the power system. With PMU technology, it is easier to exchange data by creating direct links between PMUs and the control centers. This forms a higher transfer rate of data which allows the system operators for immediate reaction in case of an event. In addition to creation of mitigative actions before the damage intensifies[20].

D. State Estimation:
The state of any power system is defined by a process called state estimation. Through this process the power system integrity is maintained by allowing the system operator in making better decisions during a system event that can cause unwanted outages[2]. The process commences by attributing a value to an unidentified variable within the system, guided by specific criteria derived from empirical data. Based on statistical methods, a state estimation of the system is conducted where the actual values are substituted by estimates within a predefined maximum/minimum threshold[7]. SCADA systems are used as a traditional method for the process of state estimation, where both logical and analog measurements of real and reactive power injections, and voltage and current magnitudes were obtained from the system[27].

Monitoring, analysis and control of the power system by system operators have advanced through the years by the use of PMUs which are considered an imperative tool used in operation[22]. The incorporation of the SCADA systems and PMUs proposed improvements in state estimation. Bus voltage phasors and line current phasors were used for more accurate data. Furthermore, due to the synchronization of PMUs with GPS, the timing of data acquisition scans becomes irrelevant[27]. The state of the system is calculated from the data collected with the system impedance model, to give out an accurate representation of the bus voltages and power line flows throughout the power system[2].

Nowadays, the implementation of PMUs with the expansion of telecommunication systems, had given for the possibility of having a dynamic state estimation of the power system. With the help of existing software and distributing a limited number of PMUs at key locations in the network, gives the system operator the full visibility of the system[7]. This facilitates the maintenance of a safe power system operation at all times and enables prompt decision-making in the occurrence of a system event that would jeopardize the stability.

E. Advanced Situational Awareness:
Situational Awareness and monitoring is one of the major applications of PMUs on WAMS[22]. The primary objective is performing an in-depth post-event analysis for the identification of the root causes and prevention of any disturbance that could jeopardize the system stability. PMUs located all across the power system enables the operator to have a real-time adequate system understanding, better information visualization and display, in addition to sharing between neighbouring operators and the means to provide diagnostic support at any moment if required[29]. Advanced situational awareness will facilitate the integration of EMS and PMUs, providing system operators real-time monitoring of the grid and prompt alarm activation in response to abnormal system conditions which will ease the decision-making processes[12, 22].

F. Advanced Applications:
Nowadays, with further advancements in R&D sectors possible studies on different applications start to emerge, for example, System Protection Integrity Schemes (SIPS), special protection schemes (SPS), remedial action schemes (RAS), under voltage load shedding and out-of-step detection and mitigation, are all used with the assistance of PMUs for the protection, and provide countermeasures of the power system[12].

2.5 Continental Europe Separation: ENTSO-E & UCTE Reports

Two events in the past years had led the Continental Europe power system to split into several subsystems due to several disturbances. In both cases it had led to severe consequences for example power deficit, under frequency, overloading of transmission lines, etc.. Fortunately these events were managed in time by the Transmission System Operators (TSOs) for the restoration of the power system before it had led to wide blackouts across Europe. Furthermore, investigations concluded that the split of the power system did not reveal any severe impacts on the market or customers. No out of range anomalies were detected and the values did not exceed the agreed Net Transfer Capacities between countries. The market continued operation as planned before, during and after the incident had occurred [4]. Below is a brief summary from two reports made about the events and what remedial actions were implemented by the TSOs:

2.5.1 System Disturbance on 04 Nov 2006

Disturbances in the grid impacted the Continental Europe transmission system, leading to a system split on the evening of 04 November 2006 for approximately two hours. Significant power flows from East to West were observed, driven by international power trading and the exchange of wind energy within Germany[3]. However, these flows were disrupted during the event, resulting in the tripping of multiple high-voltage lines[3]. As a result, the grid was split into three synchronous areas (West, North-East, and South-East), each experiencing substantial power imbalances.

This separation had caused the areas to experience under and over-frequency as can be seen in figure 2.3 below[37]. Both West and South-East areas underwent under-frequency, where it caused huge imbalances between supply and demand due to several generation units connected to the distribution grid experiencing a trip. While in the over-frequency area i.e. North-East, the system conditions deteriorated significantly with drastic overloading of high-voltage transmission lines due to the lack of sufficient control over dispersed wind and combined-heat-and-power generation units[3].

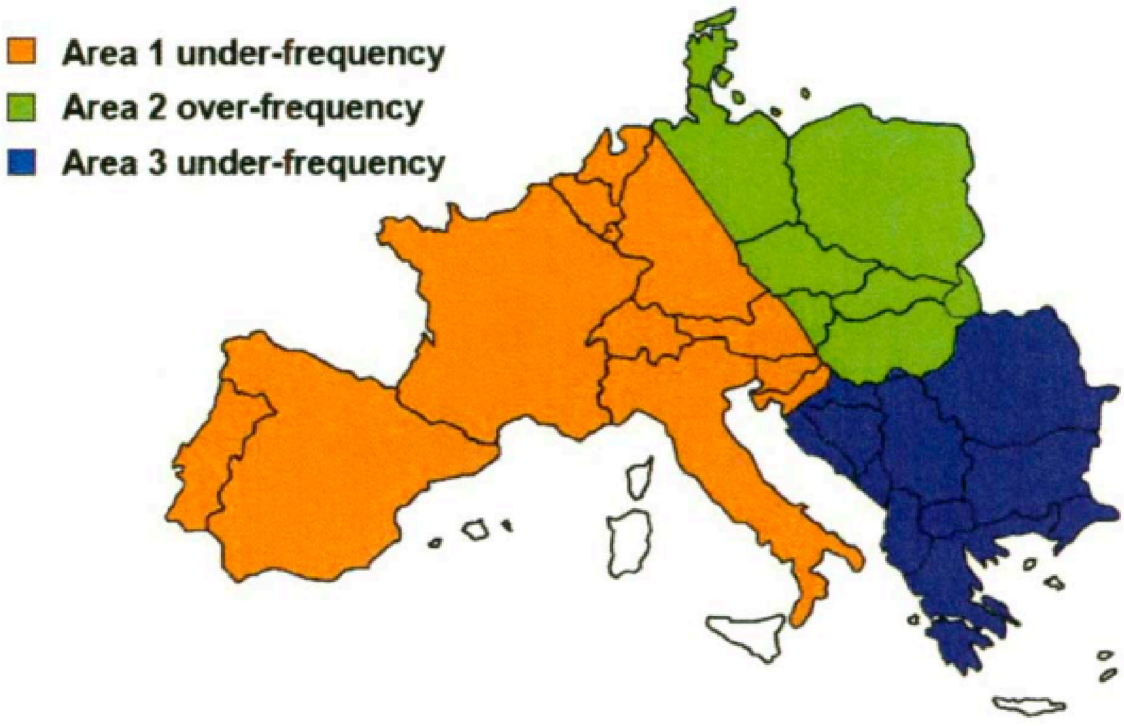

Figure 2.2: Continental Europe Split into three areas[3] ©2006 ENTSO-E. Permission obtained for reuse, courtesy of ENTSO-E transparency platform and Creative Common Attribution 4.0 International License (CC-BY 4.0)

2.5.1.1 Resynchronization Process

The actions that were made to resynchronize the system were performed within TSOs that were located in countries close to the points of the split. A decentralized approach was taken, in which preparations in coordination with other TSOs to switch the tripped lines were done independently[3]. The actions enabling for resynchronization can be classified into three phases[3]:

- A few resynchronization attempts that did not achieve real interconnection
- Real interconnection after resynchronization trials but subsequently failed
- Successful resynchronization process

Frequency measurements from WAMS were taken at different points during the resynchronization phases of the system until successful process was obtained. This can be depicted from figure 2.4 below[3] that classifies the actions that were taken at the different phases before resynchronization[3].

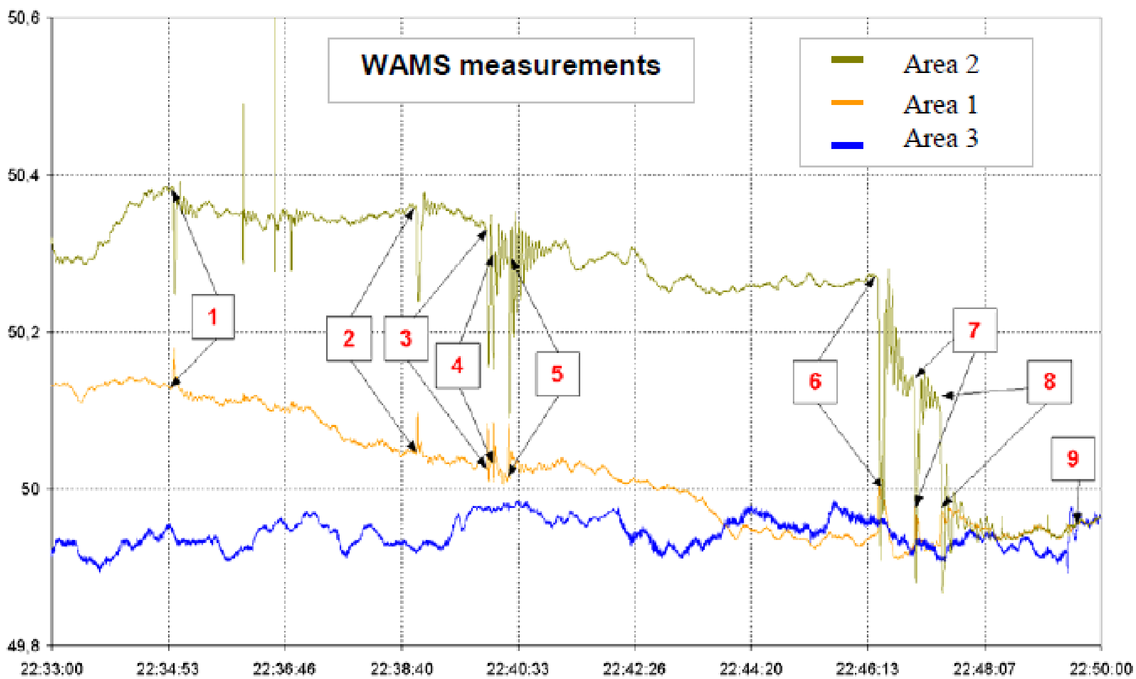

Figure 2.3: Frequency recordings for the three areas[3] ©2006 ENTSO-E. Permission obtained for reuse, courtesy of ENTSO-E transparency platform and Creative Common Attribution 4.0 International License (CC-BY 4.0)

Phase 1 of the actions are portrayed by points 1-5 in the figure, where the resynchronization process was initiated by TSOs but due to difference in frequencies that created strong oscillations, the interconnection did not occur[3]. While points 6-8 described phase 2 of the resynchronization process. This gave the system a chance to regain interconnection but was not fortunate as a few seconds later, the link was severed again due to oscillations[3]. Point 9 in the figure is where the last phase was commenced and the system regained synchronization successfully. As referred to from the figure, points 1-8 were aimed to resynchronize area 1 and 2 and subsequently after it was successful, the immediate resynchronization process with area 3 was initiated and resulted in a success[3].

Nor extraordinary climatic conditions or technical failures had caused for this separation of the interconnected system, but it was rather triggered by causes in a network distribution operator located in Germany. Once the cascaded trip of the lines was occurring, it was seen that the split of the interconnected system was happening on a fast pace and could not be stopped. Fortunately, the fast separation avoided subsequent damage of equipments caused by high mechanical forces which could have led to much greater financial damages[3]. Due to adequate performance of the TSOs, countermeasures were activated and issued at a UCTE level in every individual control area that was affected, a Europe-wide-blackout was evaded.

2.5.2 Synchronous Area Separation on 08 Jan 2021

On 08 January 2021, the cascade trip of several transmission network elements has led to the separation of the Continental Synchronous Area in Europe into two areas(north-west area and south-east area). This resulted in a surplus of power in the south-east area leading to a frequency increase while the north-west area had experienced a deficit in power which in turn led to frequency decrease[4].

Three aspects had characterized the separation phenomena in which are[4]:

- A rapid voltage collapse at all substations close to separation line
- The voltage phase angle difference experienced a fast increase between the two areas
- Difference of frequency between the two areas were gradually increased

This began with a current exceeding the specified limit on a substation's busbar coupler located in Croatia. The substation had exhibited a high load flow which led to initiate the protection scheme, therefore in turn to trip. Subsequently, two transformers had experienced overloading which led to their trip. This course of events had affected the Serbian line, which caused a large flow pattern between the two areas. Afterwards, 12 trip events on other transmission elements were initiated due to overcurrent protection that concluded in the separation[4]. PMUs, installed at substations where the separation had occurred, gave out real-time frequency recordings of the system before and after its split into two synchronous areas which can be illustrated in figure 2.5 below[4].

Investigators determined that the system was already at a pivotal point of angular stability before the initial event. Thus, the system became unstable after the first trips which led to the cascading trips. The frequency deviations in both areas were stabilized after the start of the frequency containment reserves which contributed to the power flow shortly after separation. The resynchronization process was initiated immediately after the frequency stabilization by coordinated instructions between TSOs in both areas[4]. The process can be combined through a series of preparatory actions and resynchronization sequences. Initially, the wait for the

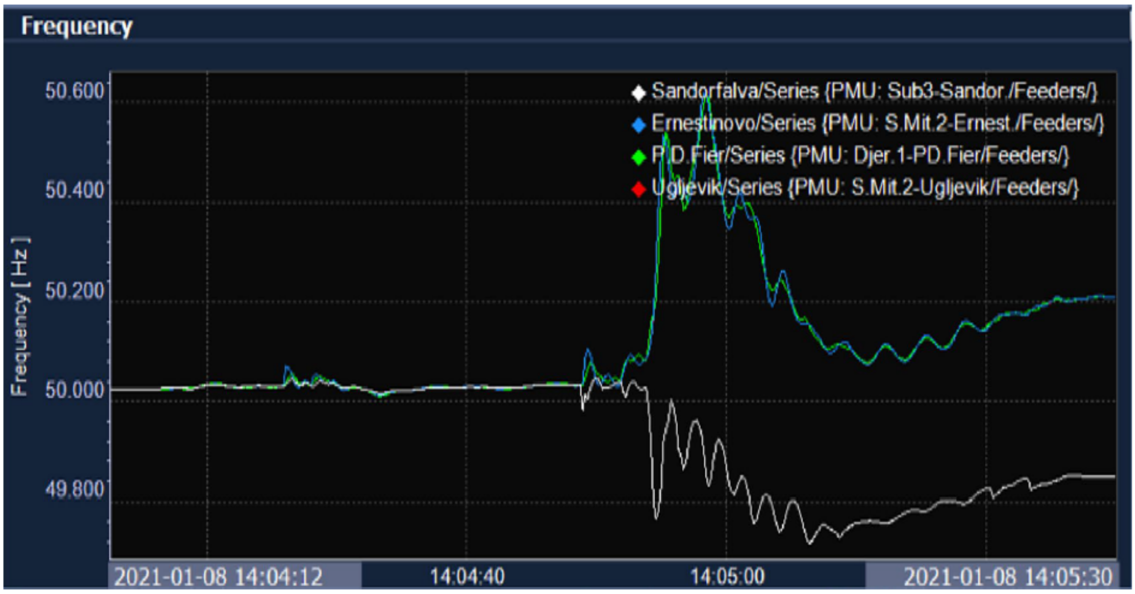

Figure 2.4: Frequency recording at the moment of separation[4] ©2021 ENTSO-E. Permission obtained for reuse, courtesy of ENTSO-E transparency platform and Creative Common Attribution 4.0 International License (CC-BY 4.0)

frequency deviation to decrease to less than 100mHz and demonstrates a declining trend. Meanwhile, standby preparations for connecting three strong reconnection points as quick as possible. The first reconnection point was the busbar coupler located in a substation in Croatia which is roughly positioned along the center of the split line[4]. Figure 2.6 below illustrates the frequencies captured on the WAMS system during the first point of reconnection that was made which in turn led to resynchronization[4]. Afterwards, through keeping an open line of communication between interconnected TSOs for the preservation of the first three lines of connection. This made it possible to commence the resnchronization sequence where finally the Continental Europe power system had regained synchronization after approximately an hour of its separation[4].

2.5.3 Outcome of Reports

The outcome of the reports revealed that the separation of Continental Europe was due to several factors. Firstly, the fact of inadequate execution and fulfillment of N-1 contingency calculations between TSOs within their own control area and contingencies located outside with coordination with other countries TSOs[3]. In addition, due to insufficient presence of information, the modeling of multi-busbar systems was inaccurate because it was treated as a single node in the system rather than multiple nodes as intended. Which also affected the possibility to perform an automatic N-1 analysis for outages or overloads[3, 4]. Finally, even though the measures implemented by TSOs to avert further damage and restore stability to the system amid an impending widespread blackout proved effective within the necessary time frame, the communication and coordination between inter-TSOs were notably slow and insufficient[3, 4].

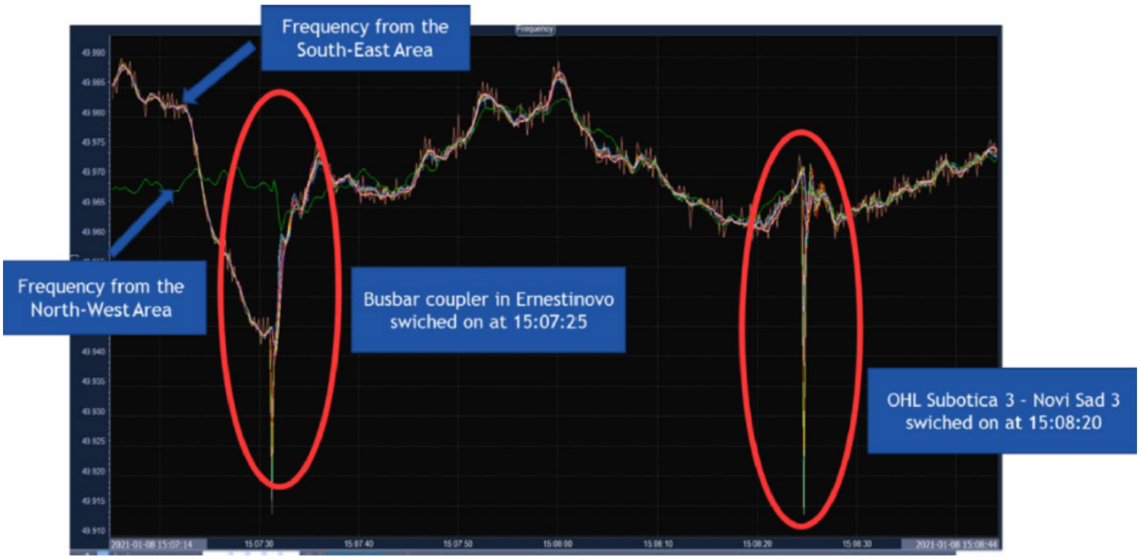

Figure 2.5: Frequency recording during resynchronization at two points[4]. ©2021 ENTSO-E. Permission obtained for reuse, courtesy of ENTSO-E transparency platform and Creative Common Attribution 4.0 International License (CC-BY 4.0)

This indicates the use of a larger scale WAMS is beneficial and necessary for monitoring, protection and control of the power system. Additionally, for avoiding issues that may arise in case of an event or a disturbance that could jeopardize the stability of the system. The deployment of PMU sensors across the power system would effectively give a clearer overall picture of the observability and controllability area of the power system. Furthermore, the tracking down of real-time states of elements in the network would be easier[21].

2.6 Continental Europe System Model

Continental Europe power system model was used in this project. It was provided by ENTSO-E System Protection and Dynamics (SPD) experts based on physical considerations and experts knowledge of the European power system dynamic behaviour. The primary aim of the Dynamic Study Model was to establish a resilient, straightforward, transparent, and readily transferable dynamic model capable of generating similar results across a wide range of dynamic simulation tools utilized by various TSOs in Continental Europe[18].

For this purpose a load-flow model of the Continental Europe system was expanded with standard models for generators and appropriate controller models in order to represent the dynamics of the interconnected power system. As a result, the model allowed for the investigation of frequency transients and general oscillatory behaviour of the power system. In addition, it can be useful for conducting detailed investigations, for example, local voltage transients. However, a detailed model of the specific affected local area has to be provided by the TSOs for model accuracy and ensuring an accurate outcome. Therefore, a detailed investigation is possible by the use of the dynamic study model[18].

The parameters and settings described below, are a result of the study of the European grid behaviour and complex evaluation of dynamic clusters of this system; so these settings can differ from “classical” literature typical numbers. Tests and comparison of the standard models in different simulation tools was already published on the ENTSO-E website[19]. Consequently the following reference dynamic standard models were set up:

- standard synchronous machine with round rotor
- automatic voltage regulator (AVR)
- power system stabilizer (PSS)
- prime mover (GOV) representation.

The Dynamic Study Model scope makes it possible and suitable for certain applications within a power system[18] which are represented below:

- Mean frequency transients (system inertia, frequency containment reserve)
- Dominant inter-area oscillatory behaviour (i.e. mode analysis)

Although, this model should reflect the typical "mean" dynamic behaviour for the whole Continental Europe interconnected power system. Certain limitations are taken into account[18], where the model does not properly represent:

- local phenomena such as voltage transients
- system protection of lines, generators and other devices
- special protection schemes and defense plans
- specific particular control schemes (AGC, islanding regulation, emergency overfrequency control, overfrequency control, under/overexcitation controls, etc.)
- dynamic load behaviour
- specific models of devices connected through a power electronic interface

This implies that for specific studies to be conducted effectively, a precise and accurate local representation of the power system, along with corresponding detailed settings, must be provided. This process is carried out in consultation with the SPD Group.

Furthermore, additional data adjustments can be made to simplify the model and ensuring its availability for third parties if necessary. Implementing these simplifications in such a way that the TSOs as single entities together with their tie lines are identified and will not affect the dynamic behaviour of the power system. A few simplifications steps were performed as[18]:

- reduce parallel lines
- reduce coupled busbars to single busbar
- unify line and transformer limits
- anonymise geographical names

- aggregate loads

The major benefit of the Dynamic Study model lies in its ability to provide comprehensive topology information for the synchronously interconnected power system of Continental Europe, taking into account its dynamic aspects. This information is considered essential for analysis of global phenomenon in stability studies. Additionally, the development of a detailed model in accordance to local phenomena examination within the defined "observability area", while preserving the system's overall frequency behaviour. Furthermore, the development process of the dynamic study model can be replicated and implemented on other power systems as a guidance for further studies[6].

2.7 The Nordic44 Power System Model

The Nordic 44 model is an accumulated dynamic power system simulation model designed to study and analyze the dynamic phenomena in the Nordic power grid[33]. It plays a significant role in many research projects performed to study the power system stability ensuring the operation and reliability during the occurrence of events.This model can be useful to electricity market operators who can acquire key data regarding pricing, production and transmission capabilities for energy tradings. Studies are conducted on the Nordic44 power system model for transition to a cleaner and robust energy system while accommodating increasing penetration of renewable energy [33].

This Norwegian University of Science and Technology (NTNU) were the first to initially develop this network which had also gone through many iterations before reaching its present state [33]. The version that will be used in this project, is a based on a version that has been provided by the Swedish Transmission Research Institute (STRI). Its availability in softwares like PSS/E and DIgSILENT Powerfactory makes it the perfect network to perform simulations[33]. In case of the unavailability of the Continental Europe model, the Nordic model will be used for this project to study the capability of the system to regain synchronism after a following disturbance which led the large interconnected power system to split into several subsystems.

3

WAMS Simulation & Modelling

In this chapter, the modelling and implementation of the methods used are covered along with reasoning for each choice.

3.1 Modelling and Software

3.1.1 PSS®E

PSS/E software which is developed and preserved by Siemens is used in this thesis as well as being used all across the world. Load flow computations, fault analysis, optimal power flow, dynamic analysis and much more can be made using features of PSS/E such as graphical interface[34]. In addition, to the Psspy application programming interface (API) which allows for the integration of Python and PSS/E for facilitating extended automation and program control for advance users[34].

3.1.2 Psspy Python Framework

PSS/E graphical interface favours python for the interaction with the PSS/E software. Case studies were ran using simple scripts written from a Python-class[34]. PSS/E is controlled by this Python-class through the use of Psspy. This allows for model initialization, changing of the parameters and the ability for several simulations to run simultaneously and the automatic creation of desired plots for use by the user[34].

3.1.3 N44 model

In order to observe how the system reacts to different methods of resynchronization during static and dynamic load flow simulations, a simplified aggregated network model of the Nordic system is used. It has 44 buses of which it contains 46 generators comprising of 300 kV and 420 kV voltage levels, 15 transformers, 43 loads and 67 branches, however 3 additional distribution buses were added to a bus located in southern Sweden by Lund university bringing the total into 47 buses. These minor modifications portrays the Nordic system in a lower detail than the models that have thousands of buses and branches represented by Nordic TSOs. Due to the reduced number of components, the computation costs are reduced, in addition to increasing the manageability which in-turn simplifies the simulations of complex interactions between the generation, transmission and distribution.

The power system model covers the grid through Norway which comprises of 8 regions (NO1-NO8), Sweden with 4 regions (SE1-SE4) and Finland with 2 regions (FI1,FI2). A map of the interconnected network of Northern Europe and a single line diagram for the model in PSSE are found in appendix 1. All generator dynamic models are "GENSAL" and "GENROU" being salient pole generator model and round rotor generator model respectively, representing the dominating hydro or nuclear/other thermal plants of each bus. In the east part of Sweden (SE3), the swing bus is located at bus 3300.[41, 42]

3.2 Static Load flow modifications

To stress the system above its normal operation, some minor modifications were made to the parameters of the model without entirely changing the topology(i.e. line characteristics, transformers data) of the model itself. These modifications allowed for better observation of the fluctuations of the variables (i.e. voltage, frequency, angle and power) throughout the course of the simulations.

3.2.1 Bus voltages

The voltage levels at different nodes or buses in the network are represented by the bus voltage, however factors such as load demand, generation output and the network topology can cause changes in these voltages. Therefore, constant monitoring, control and adjustment are done to keep the bus voltages within acceptable limits. This is done for ensuring the stability and proper operation of the power system.

For commencing the simulation, the voltage setpoints of the buses have been reduced to a lower value than the normal operating condition. Although reducing the voltage setpoints of the buses have its effects on the power system, some may include:

- Voltage Instability: where the model struggles to maintain the acceptable voltage levels which causes equipment failure.
- Overloading Equipments: more current is drawn from transformers required to maintain the power levels. This results in overheating of the devices
- Loss of loads: loads may experience voltage sags or even outages
- Reactive Power Demand: low voltage levels increases the demand of reactive power in the system, where it can decrease to the point of no return.
- System resilience: Changes in the voltage levels can cause cascaded failures across the power system

This reduction was necessary to stress the system above the normal operating conditions. As a result, none of the machines or buses have exceeded the operational limits. Two main purposes were achieved from doing this step; (1)stressing the system above normal conditions, (2)observation of more oscillations of the bus voltage during the dynamic simulation resynchronization phase. Other alternatives can also be used to stress the system, such as adjusting the droop of the governors to result in different frequencies across the generators. This will also affect the voltage and the angle differences between different parts of the system. Although this could be an effective method, however it was not done so as not to change the topology of the system.As can be shown from table 3.1, the system bus voltages are reduced to a lower value than the original value. Although this reduction can be considered small but it impacted the power system without overloading of components or lines, in addition, the system power flow solution was found under these constraints.

Table 3.1: Bus Voltages

Bus	Voltage before	Voltage after	Bus	Voltage before	Voltage after
1	1,0271	1,0000	5401	1,0052	0,9000
2	1,0271	1,0000	5402	1,0044	0,9000
3	1,0271	1,0000	5500	1,0100	1,0000
3000	1,0000	0,9000	5501	1,0067	0,9000
3020	0,9969	0,9000	5600	1,0100	1,0000
3100	1,0298	1,0000	5601	1,0206	1,0000
3115	1,0000	0,9000	5602	1,0072	0,9000
3200	1,0297	1,0000	5603	0,9750	0,9000
3244	1,0001	1,0000	5610	0,9731	0,9000
3245	1,0000	0,9000	5620	1,0091	0,9000
3249	1,0000	0,9000	6000	1,0050	0,9000
3300	1,0000	0,9000	6001	1,0027	0,9000
3359	1,0000	0,9000	6100	1,0000	0,9000
3360	0,9984	0,9000	6500	1,0000	0,9000
3701	1,0048	1,0000	6700	1,0200	1,0000
5100	0,9853	0,9000	6701	1,0066	1,0000
5101	0,9871	0,9000	7000	1,0000	0,9000
5102	1,0024	1,0000	7010	0.9969	0,9000
5103	1,0023	1,0000	7020	1,0000	0,9000
5300	1,0000	0,9000	7100	1,0000	0,9000
5301	1,0042	1,0000	8500	1,0200	1,0000
5304	1,0081	1,0000	8600	1,0200	1,0000
5305	1,0132	1,0000	8700	1,0200	1,0000
5400	1,0070	0,9000			

3.2.2 Generation altering

Altering the generation output of the generators in a balanced power system can have several effects, some of which:

- Power flow changes: increased or decreased power flows through the transmission lines through the branches of the power system
- Voltage regulation: by increasing the power output, higher voltage profiles are produced throughout the system
- Operational constraints: the increase pushes the components of the power system beyond its capacity
- System stability: the stability margins of the system may encounter difficulty in maintaining its stability in case of a sudden change or a disturbance.

To affect the system stability resulting in a stress of the system's operational limits, generator "G1" located at bus 3245 in SE2 was increased from 1500 MW to 2200 MW. The extra 700 MW produced by the generator was distributed across the system with most of the power being fed to bus 3000 in SE3. Two parallel lines connecting bus 3245 to bus 3000 in SE3 had reached their loading capacity.

3.2.3 Evaluation of outcome

An observation was made, that the Nordic44 model provided was created in such a way that the loading capacity of most of the lines connecting the branches together across the whole Nordic power system did not exceed 50% of its total loading capacity. This made it extremely difficult to stress the system as much as possible without experiencing either overloading in some lines or the whole systems blows up without meeting its convergence criteria. Changing the topology of the model was also viable but that meant straying away from performing the simulations on an approximate model of the Nordic system compared to today's model, which was not sufficient to provide approximate real data and results.

By performing the modifications mentioned above, the model has experienced a reduction in the scheduled voltage and the loading capacity, of two parallel lines connecting bus 3245 in SE2 and bus 3000 in SE3 and a transformer located between bus 5501 and 5500 in NO1, has reached its limits. This small modification was enough to create the disturbance needed to perform the simulations. Table 3.2 displays the loading capacities of the lines and the power exchange between the lines connecting the two buses between SE2 and SE3. A huge spike in power can be noticed when comparing the differences between the initial and the modified power flow through the lines between the buses. In addition, the transformer connecting bus 5501 to 5500 had reached a loading capacity of 97%. Moreover, the power exchange between the regions SE2 and SE3 has also increased from 1060.1 MW initially to 1661.1 MW which is normal due to the increase of the generation output of "G1".The modifications made did not affect the operation and the response of the system due to this increase in generation and decrease in voltage setpoints. Table 3.3 depicts the total power exchange between the three countries before and after the modifications were made to the model. It can also be noticed that there is a slight change between the power values which can be overlooked.

Table 3.2: Loading capacity & Power exchange

Bus	Loading Capacity		Power Exchange	
3245–>3000	Before	After	Before	After
Line1	69%	99%	831.5MW	1188.7MW
Line2	62%	89%	497.7MW	711.8MW

Table 3.3: System power exchange

	Power Exchange	
From–To	Before	After
NO–>SE	1060.1MW	1059.7MW
SE–>FI	1266.5MW	1267.0MW

3.3 Dynamic Load Flow Modifications

Dynamic simulations involves modeling the time-varying behaviour of a power system under transient conditions. It is the gate into understanding and analyzing the system stability, its response to disturbances and the dynamic interaction between the components of the power system. It is considered essential for grasping the concept of how real power systems operate amidst an event threatening the stability and reliability of the power system.

3.3.1 Dynamic data file

PSS/E provides a range of tools and functionalities to facilitate dynamic simulations. During execution of these simulations, an error was initially detected in the dynamic data which if not fixed, would reflect on the expected system behaviour and would result in false outcomes.

While performing the simulations an "Initial condition Suspect" was noticed by PSSE and was located in the south of Norway, specifically two generators in bus 5600, in Kristiansand (NO3). The error turned out to be a typing error in the dynamic data file while led PSS/E to suspect an error with the states of the exciter models "SCRX" and "SEXS", being bus fed or solid fed static exciter and simplified excitation system model respectively, while performing certain dynamic operations which were necessary for initializing the system before commencing the dynamic simulation. Since these two exciter models are related to the generator model "GENSAL" as their collection gives a comprehensive representation of the synchronous generator and its excitation system. Looking back at the parameters of "GENSAL", it was noticed that the value of the dq-axis sub-transient reactance "X”d" and "X”q" measured in per unit was inputted incorrectly which interfered with performing the simulations.

After reviewing and examining the initial conditions associated with the models and checking the model parameters, an adjustment of changing the sub-transient reactance to an acceptable value that would reflect for a better expected system behaviour. The simulation was repeated and verified to ensure normal initial conditions of the system, yielding a success. Table 3.4 shows the value of the sub-transient reactance before and after the amendment.

Table 3.4: Sub-transient Reactance in p.u.

	Before	After
X”d=X”q	0.28	0.2856

3.4 System Split

Splitting the Nordic system into power balanced subsystems is a complex task that requires an extensive analysis of several critical factors to ease the understanding of how the system operates and facilitate an approach for creation of the split and resulting in operational stability in the subsystems. A combination of two approaches for achieving this goal is used, which include examining the distribution of the power generation in the Nordic System and targeting the lines with the lowest loading capacities to initiate a disturbance. Taken into more detail, these approaches are described below:

A. Power Generation Analysis:
The power generation mix in these countries is characterised by a strong emphasis on renewable energy sources. Evaluating the distribution of power generation across the Nordic system ensures that each subsystem does not only remain within its transmission capacity limits but also maintaining the power balance within the subsystem. This can be done by mapping the locations where the power generation is concentrated within the system.

B. Low Loading Capacities of Lines:
Verifying the critical branches for the power flow can indicate weak points in the line where it can ease the separation of the Nordic system. Tripping of the transmission lines with low loading capacities is a logical approach since their limited ability to handle large power flows, they often act as weak links in the network. Although disconnecting them would have less impact on the system stability but they serve in maintaining the voltage stability and preventing cascading failures.

By changing the network configuration and taking these two approaches in mind, the system split was accomplished. Figure 3.1 below shows the separation of the Nordic system into two power balanced subsystems. Additionally, it shows the approximated location of the nine transmission lines in the Nordic countries that were tripped during the disturbance to create the two synchronous areas. One line located in Norway while the other 8 transmission lines in Sweden.

The split was created by tripping of several transmission lines in Norway and Sweden with low loading capacities. In total, 9 lines were tripped for the creation of the subsystems comprised in the two areas. Table 3.5 below depicts the loading capacity of the transmission lines that were tripped connecting the buses in both countries and in addition to the power exchange between them before the split. The lines were tripped on the premises of an equipment maintenance, to be specific routine checkups

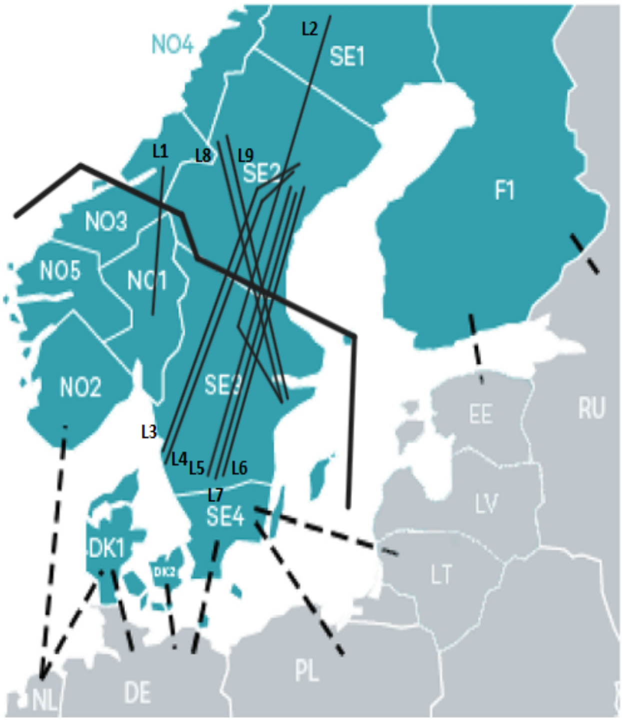

Figure 3.1: Map of Nordic System[60] Addition of split line and 9 transmission lines to indicate the separation. ©2021 Wei Li, Denis Mike Becker. Permission obtained for reuse, courtesy of Elsevier and Copyright Clearance Center

of the transmission lines. Their trip had impacted the stability of the power system. As can be noticed from the table, this maintenance has occurred in the 7 lines with a low loading capacity, hence the the lasting two parallel lines which have already reached their maximum loading capacity were overloaded and therefore tripped as protection. Additionally, the table depicts the total power exchange between the two areas (i.e. from Area 1 to Area 2) which in total gives -1543.2 MW. This indicates that Area 1 is at a deficit of power, in which Area 2 is generating the surplus and compensating for Area 1 deficit by the 1543.2 MW needed.

Table 3.5: Nine Tripped Transmission Lines

Line No.	Bus(From->To)	Region	Lines	Loading Capacity	Power flow before Split
1	5100–>6500	NO6–NO7	Line 1	13%	88.2 MW
2	3000–>3115	SE3–SE1	Line 1	24%	-54.5 MW
3	3359–>3100	SE3–SE2	Line 1	29%	160.5 MW
4		SE3–SE2	Line 2	38%	345.8 MW
5	3200–>3100	SE3–SE2	Line 1	11%	-67.7 MW
6		SE3–SE2	Line 2	11%	-67.7 MW
7		SE3–SE2	Line 3	11%	-67.7 MW
8	3000–>3245	SE3–SE2	Line 1	99%	-1177.4 MW
9		SE3–SE2	Line 2	89%	-702.7 MW
Total power exchange from Area 1 to Area 2					**-1543.2 MW**

3.4.1 Two Synchronous Areas

The decision for tripping of the transmission lines was made after comprehensive studies and simulations of the Nordic system which ensured the creation of two power balanced and stable synchronous areas. With the south-west area experiencing a deficit of power and a surplus of power in the central north-eastern area, leading in turn to a frequency decrease and a frequency increase in those areas respectively.

No exchange of power was noticed during the time of the disturbance. Buses 5100, 3359, 3200, and 3000 are in "AREA 1", while buses 6500, 3245, 3115, and 3100 are in "AREA 2". These buses along the split line will be monitored for synchronization data such as frequency, voltage, and phase angle for observation and synchronization purposes.

3.5 Subsystems synchronization

Resynchronization of power subsystems after a split is critical into restoring the stability of the full system. Constant communication between TSOs of countries is necessary to maintain the flow of information that aids in better decision making, in turn extends on to quick response time that leads to quicker and smoother synchronization.

3.5.1 Model Tuning

During dynamic simulations, the role for maintaining the power balance in the system shifts from the swing bus and becomes the governor's role. Since it is a collective response of all the generators and their control systems, the simulations aim to model the real world behaviour of the power system as accurately as possible. Hence the governor's dynamic adjustments allows the possibility to continuously adjust the generators outputs to match the varying load and maintaining frequency stability. Therefore, the parameters of the governors were altered to aid the resynchronization of the two areas.

Two turbine governors were given in the model: HYGOV and the IEESGO governors, their role in regulating the turbine speed and maintaining system stability which considered crucial for the operation of the power system. For purpose of the simulations, parameters for both governors will be adjusted. Specifically, the turbine gain (K1) for the IEESGO and the turbine damping factor (Dturb) and turbine gain (At) of the HYGOV governor models. These changes would give the chance to observe and analyze the system response time and operation towards various conditions and disturbances.

The modifications made for the models were implemented for generators located along the split line of the disturbance which are displayed in table 3.6 below. The reasoning behind this action was due to the location of the disturbance and the generators that were directly impacted by it. Although the disturbance affect the entire system to an extent, major deviations can be noticed in generators close by. Therefore it is considered a strategic approach focusing on the generators such that tailoring their response characteristics to better withstand and achieve impactful improvements for mitigating the transient effects of the disturbance. Moreover, the rest of the models present in the dynamic data file, i.e. all exciter models (SEXS, SCRX, IEEET2), generator models (GENSAL, GENROU) and stabilizer model (STAB1), were all left as were modeled, as it will contribute to the response of the system.

Table 3.6: Governor Parameters Alteration

		HYGOV Parameters				IEESGO Parameters	
		Dturb		At		K1	
Bus	Generators	Before	After	Before	After	Before	After
3000	G1,G2,G3	N/A				0.0	0.9
3115	G1,G2	0.5	0.7	1.0577	1.1	N/A	
3245	G1	0.5	0.7	1.01	1.2	N/A	
3359	G1-G6	N/A				0.0	0.9
5100	G1	0.5	0.7	1.1	1.2	N/A	
6500	G1,G2,G3	0.5	0.7	1.1	1.2	N/A	

As was mentioned above the turbine gains and damping factor were specifically chosen to be modified and not the other parameters due to several reasons. Firstly, adjusting the turbine gain enhances the speed control response of the governor, allowing it to swiftly oppose the effects of disturbances and maintain system stability. This parameter expresses the control signals into mechanical actions, thereby improving the turbine's ability to stabilize system frequency effectively. Similarly, modifying the turbine damping factor reduces the risk of prolonged speed fluctuations following disturbances, therefore helps control the turbine speed oscillations, ensuring a smooth transient response. Unlike changing droop settings, which affect the entire grid frequency and can lead to spread of the imbalances, adjustments to turbine gain and damping factor primarily influence the dynamics of individual generators close to the disturbance, thus providing targeted stability improvements.

Secondly, altering the turbine gain and damping factor is less complex for system operators and gives out more predictable outcomes compared to modifying droop settings, which can disrupt the overall power balance and result in significant frequency deviations or power oscillations on the power system. Adjusting these parameters can be done through control mechanisms within the governor that indirectly influence the physical characteristics of the turbine, making it easier to fine-tune the response without causing unintended consequences. While changing the droop settings has a more forceful impact on the coordination between generators, potentially leading to frequency instability and unpredictable power sharing. This forceful impact can risk the overall system frequency and stability, whereas tuning the turbine gain and damping factor ensures that the power system as a whole remains stable and reliable without affecting the entire grid frequency. Therefore, focusing on these adjustments supports localized stability and effective disturbance management.

On the contrary, if these parameters are not adjusted, several issues may arise. Firstly, slower responses to the disturbance and extended time of instability due to the ineffective ability of the governor to control the turbine speed. Secondly, increased oscillations caused by improper damping which impacts the neighbouring generators hence affecting the overall performance and stability of the power system. Finally, severe frequency deviations which can persist along the power system affecting its reliability and efficiency making it more at risk for further disturbances.

3.5.2 Resynchronization Process

The principle behind the resynchronization of two unsynchronized subsystems restoring it to one large interconnected power system requires the alignment of the voltage, frequency and the phase angle to ensure a stable reconnection. Since both subsystems are operating independently with, frequency and phase angle discrepancies, a crucial challenge would be to ensure the phase angles at the any interconnection where the disturbance had occurred are the same or within a certain acceptable error margin. This is necessary to prevent large power surges and for maintaining the power system stability. Thus, the goal is to minimize the errors within acceptable limits, ensuring a stable reconnection and perfect synchronization.

The process commences by monitoring the frequency, voltage and phase angle of each bus along the split line of the disturbance in both areas. This allows for necessary adjustments such as adjusting the generation output, managing different loads across the system, and the use of control systems to tune the parameters. The tuning that was made earlier to the governors made the possibility of the two subsystems to gradually align the subsystems operating conditions together and facilitate the reconnection of the lines. In addition to the aid from synchronization devices such as synchronizer devices leading to the resynchronization of the subsystems together, restoring system stability.

Two methods were performed and compared when trying to resynchronize the two subsystems together. Firstly, sequential resynchronization which is the reconnection of the tripped lines one at a time until full reconnection occurs and whole system operation is restored. Secondly, simultaneous resynchronization that allows for all tripped lines to be reconnected simultaneously with respect to the system response and restoration of the initial system operation. While performing simulations several points are suggested which would allow for realistic approach to be taken into mind when performing and executing these methods. The points for both methods are each described below:

A. Equivalent approaches for both methods:

Some key points will be taken into account regarding both methods which are described below:

- **Strong power links:**

For a successful reconnection, the strength of the power links between the branches is taken into account. For initial reconnection, stronger links are preferred as they provide a back-bone and support for balancing the power and stabilizing the system. The links are chosen as their ability to withstand higher power transfers without becoming overloaded. They maintain the integrity of the power system during this delicate situation which enables the operators a smooth resynchronization and reduce the risk of failures.

- **Synchronization information:**
  Information about the frequency, voltage and phase angles of the buses and generators between the subsystems should be carefully monitored, which are considered essential for the alignment of these parameters. The speed at which the information is recieved will be dependent on the used reconnection method.

- **Contingency plans:**
  In case of unforeseen issues that can not be predicted by TSOs, preparations must be done to quickly respond to and mitigate the problem if it arises, therefore protecting the stability of the power system.

- **Operational status:**
  The operational status of generators and loads in each subsystems must be within stable limits. This ensures that the load demands are balanced while the generators are not operating under stress.

- **Synchronizers:**
  Synchronizing devices referred to as synchronizers are devices used for reducing the frequency, voltage and phase angle differences between the disconnected parts of a system before the reconnection so as to match and synchronize the disconnected sections at the instant of resynchronization. Devices such as SYNCHROTACT 6 designed by ABB[49] and SIPROTEC 7VE85 designed by Siemens[50] are a perfect example, where by examining the recommended settings that will be a guide for any voltage, frequency or phase angle values that surpass a certain limit when executing the synchronization methods.

B. Simultaneous resynchronization:
Since this method of resynchronization is based on presenting studies on WAMS and the development/testing of a PMU-based method to be used in simulations which is necessary for it achieve the required output. An assumption was taken into account that is described below:

- **PMU placement:**
  Real-time monitoring is necessary for collecting data about the system and detecting the right opportunity to initiate reconnection. Due to

the absence of actual PMU sensors, the simulations continued with the assumption that all buses have a PMU sensor installed in them. This ensures the continuous monitoring of the voltage, frequency and phase angles at different locations and with precision. In addition, it helps TSOs to identify the moment for reconnection.

C. Sequential resynchronization:
A realistic approach will be used to perform this synchronization method depending on available resources and technology provided today in the world. This approach considers real-life conditions to initiate and guide the reconnection process. The approaches used are mentioned below:

- **PMU placement:**
  Depending on the country's resources and the cost of PMU sensors, the placement of the devices would be limited to several buses along the entire network. The exact location of the PMUs is not specified throughout the process but this assumption is necessary to imitate the real-life conditions.

- **Communication delays:**
  Since the model is considered as a large interconnected system with different generators and loads distributed across the countries, the possibility for communication delays (i.e. exchange of information) between TSOs in the different countries is taken into account as it can impact the response time and coordination of TSOs towards the resynchronization. Minor delays could disrupt the reconnection efforts made by TSOs for resynchronization. Therefore this coordination is considered particularly of great importance when managing the synchronization of the subsystems.

By following these approaches the resynchronization for both methods is executed and the parameters for both cases were measured and compared. The results for the simulation are presented in the following chapter.

4
Results & Discussion

This chapter presents and analyzes the results obtained for both resynchronization methods. The purpose is to demonstrate the effectiveness of simultaneous synchronization method over the sequential. To demonstrate this, voltages, frequencies, phase angles and power flow from both methods will be monitored.

4.1 General Information

Dynamic load flow analysis was conducted on the model. The system ran at normal conditions for 3 seconds. The disturbance (i.e. tripped lines) was then initiated and the simulations continued running for additional 27 seconds. At the 30 second mark, the resynchronization methods were executed each separately to see how the system responds to the caused events. The total simulation time is 130 seconds.

Since the main focus was on buses that are located along the split line where the disturbance had occurred. Through the whole duration of the simulation, synchronization information such as bus voltages, frequencies, phase angles and power flow between the branches, were extracted from adjacent buses that have common transmission lines i.e. bus 3000, 3115, 3245, 3200, 3100, 3359, 5100 and 6500.

4.2 Simultaneous Resynchronization

This method emphasizes the use of PMU sensors for monitoring and extracting data which provides accurate and real-time information for TSOs that aims to react and mitigate any event that can occur throughout the whole power system, in which this case will be realigning the subsystems in a single step.

4.2.1 Voltage & Frequency profiles

The voltage profiles for the simultaneous method illustrates the response of the system during the occurrence of the disturbance to the point where the reconnection is achieved. Figure 4.1 below depicts the voltage at bus 3000 located in area 1 with comparison to its adjacent bus 3245 in area 2. The frequencies of the two buses clearly displays the difference between the two areas as one experienced frequency increase while the other undergoes a frequency decrease. Figure 4.2 presents the frequencies over the duration of the simulation.

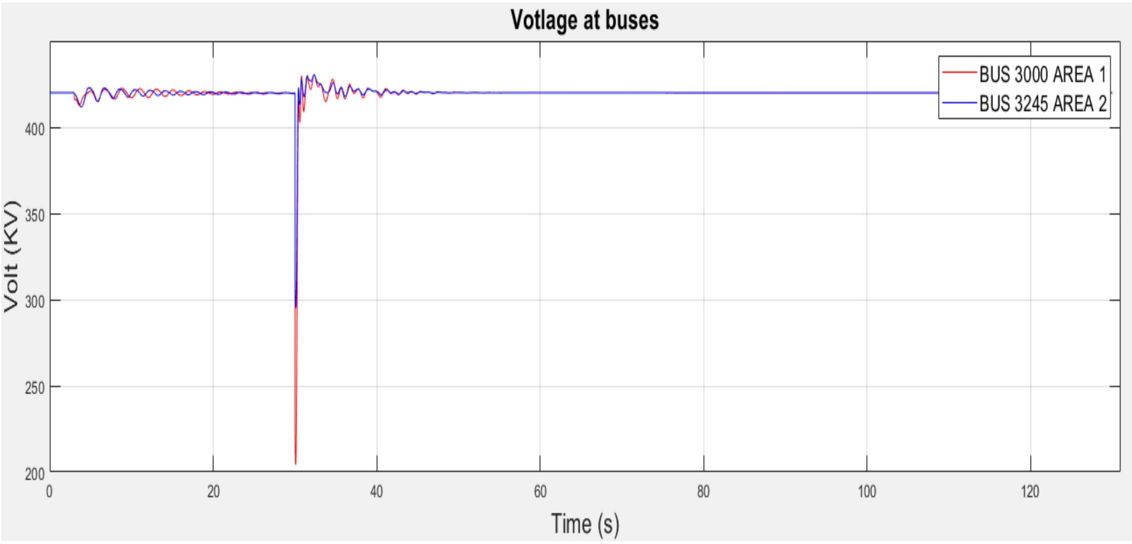

Figure 4.1: Voltage recordings of bus 3000 in SE3 & 3245 in SE2

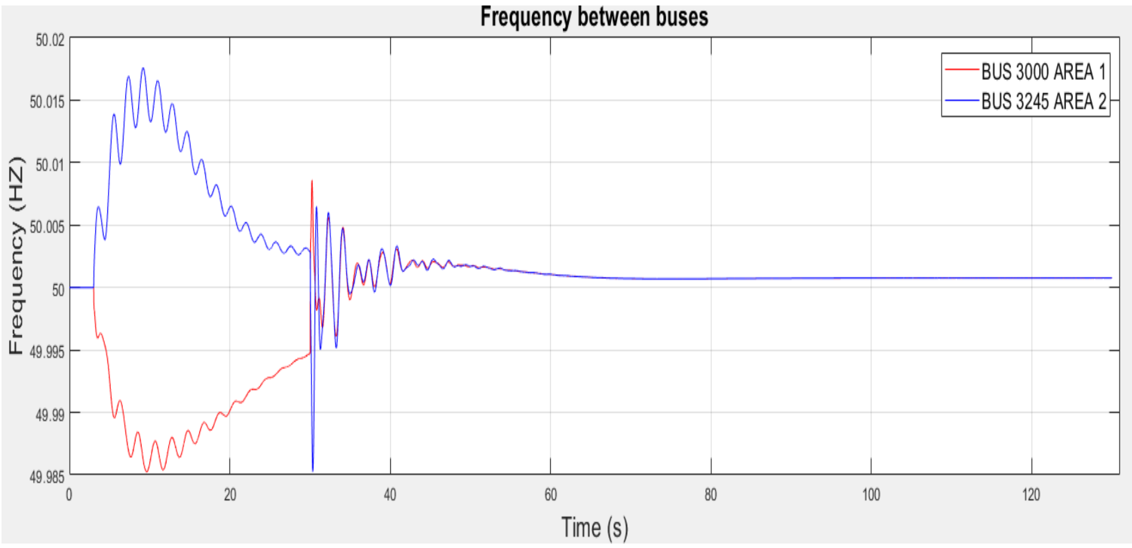

Figure 4.2: Frequency recordings of bus 3000 in SE3 & 3245 in SE2

As can be seen from the figures above, Area 1 depicted by the red curve while Area 2 by the blue curve. Following the tripping of the transmission lines, both areas initially experienced small oscillations in the voltage of the buses, however started to stabilize as the system got accustomed to the disturbance. The frequency curves indicate that, bus 3000 in area 1 had experienced an under frequency with a downward frequency nadir of about 0.015 Hz. Conversely Area 2, encountered an over frequency of approximately 0.016 Hz. This clearly demonstrates that the two areas are both functioning with different frequencies. Both areas experienced oscillations in the frequency curves from the start when the disturbance was initiated, however the oscillations created by the split were damped as the simulation progressed in time for the two subsystems leaving the chance for the reconnection to initiate.

At the point of reconnection, in both figures it can be noticed that the simultaneous reconnection of the lines was a success from the first attempt due to the model tuning that was done. In figure 4.1, it can be seen that both buses in each area had experienced a voltage dip especially in bus 3000 in area 1. This is due to several factors when trying to reconnect two subsystems, from which are, switching transients (i.e. the act of closing the lines simultaneously) or any mismatch in load and generation that causes transient power flows that eventually affects the bus voltages, but only lasted for 0.4 seconds which is quite normal in this case with simultaneous reconnection. Considering the tuning that was made, It can be seen by the way the voltage and frequency curves of both areas start to align together until both areas resynchronize and the system returns to its normal operating condition.

Figure 4.3 and 4.4 below displays the frequency and voltage curves of bus 3100 located in area 2 and bus 3359 in area 1. The two buses are connected by two transmission lines. It can be seen that both of them exhibit fluctuations in the voltage curves. Whereas, in the frequency curves, very small fluctuations were noticed.

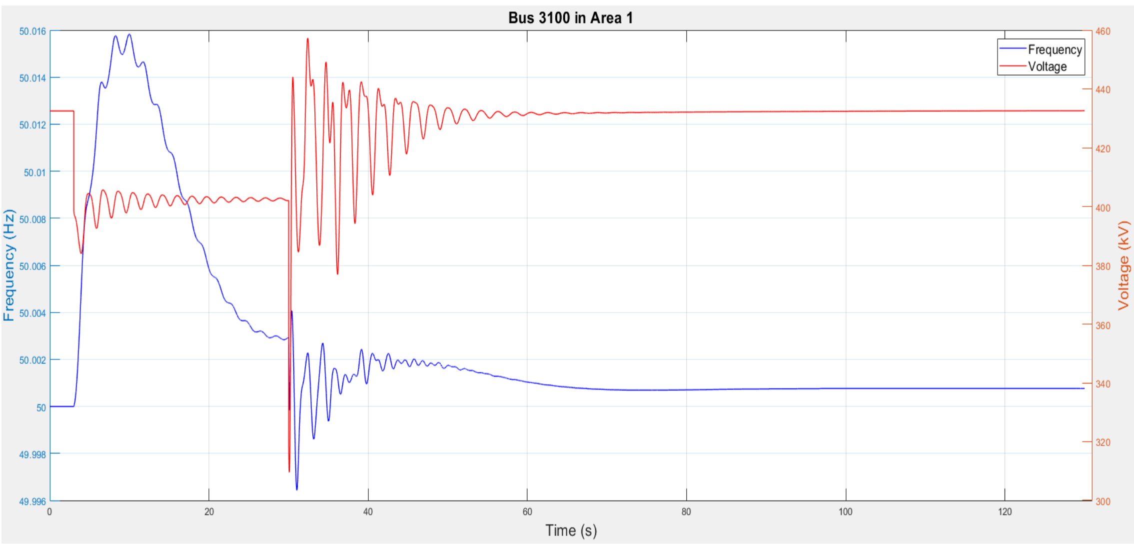

Figure 4.3: Frequency & Voltage recordings at Bus 3100 in SE2

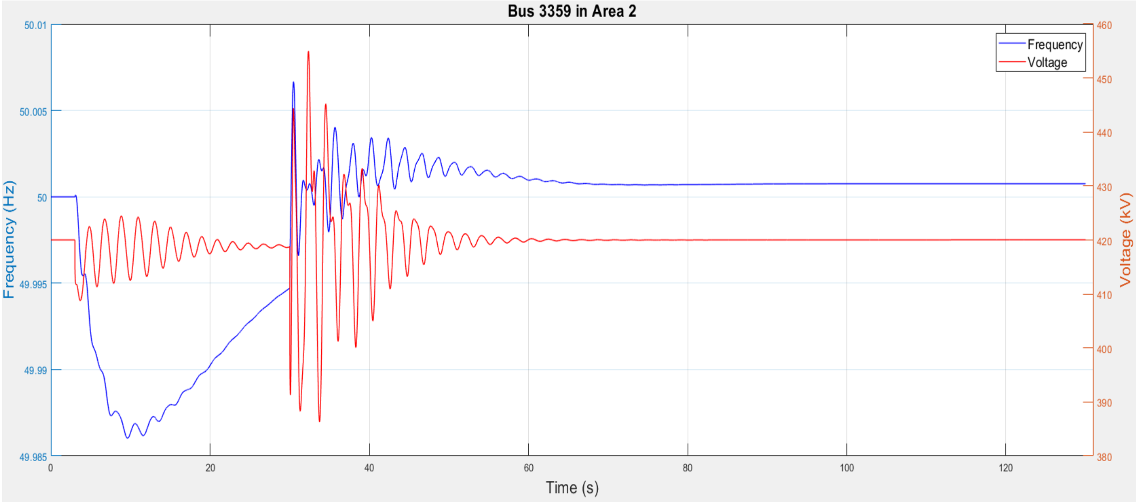

Figure 4.4: Frequency & Voltage recordings at Bus 3359 in SE3

4.2.2 Phase angle

The phase angle in itself and the angle difference between nodes in the power system are considered to be crucial for any power system. Maintaining the phase angle influences how much power gets to flow between branches of the nodes, hence preserving the integrity and voltage stability of the power system.

When the disturbance was initiated, the phase angles of the buses misaligned according to which part of the system the bus was located, where the angle of bus 3000 in area 1 had experienced a tremendous decrease until it reached a point where it stopped decreasing at the point of reconnection, where it started to increase once again. While the angle of bus 3245 in area 2 had sustained a noticeably increase in its value due to that subsystem experiencing an increase in the frequency. Figure 4.5 below depicts the bus angles before the reset method was applied.

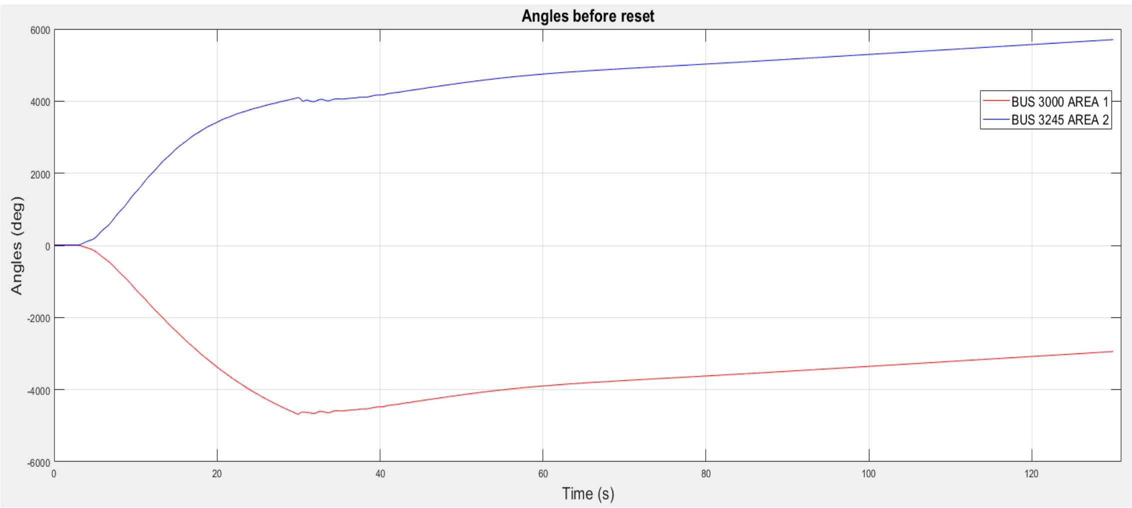

Figure 4.5: Bus angles before reset method between bus 3000 in SE3 & 3245 in SE2

This massive increase and decrease exhibited for both areas is described by the relationship between the frequency and the phase angle. Since the frequency of a power system is defined as the derivative of the rate of change of its phase angle over a certain period of time. Therefore, it can be proportionally said that the phase angle is the integral of the frequency over that period of time. Hence from the plot, it is observed that the values of the angles are between the range (+6000 & -6000 degrees), which can be shown as a result of the accumulated phase angles over the period of the simulation.

A reset method was created to reduce the accumulated phase angles of the buses in the subsystems within a desired range. It aids in ensuring that the phase angle and its difference stays within a managed range depending on the value of the phase angle at a certain period of time, respectively was reduced by multiples of 360 degrees. The desired range chosen for this method was within a ±180 degrees. The reset method is represented in the MATLAB code in appendix 2. Figure 4.6 depicts the new phase angles of the buses in each subsystem after the reset method has been applied.

Consequently, during the separation, each subsystem operates independently and any difference in the frequency between the subsystems can also be interpreted as the accumulation into the phase angle difference between the two buses in the subsystems over the time of the simulation. Therefore, the reset method was applied to the angle difference between the two subsystems for 3000 and 5100 with their adjacent buses in area 2 3245 and 6500 respectively, which is shown in figure 4.7 below. Bus 3300 located in area 1 was used as a reference for the voltage phase angle difference between the subsystems.

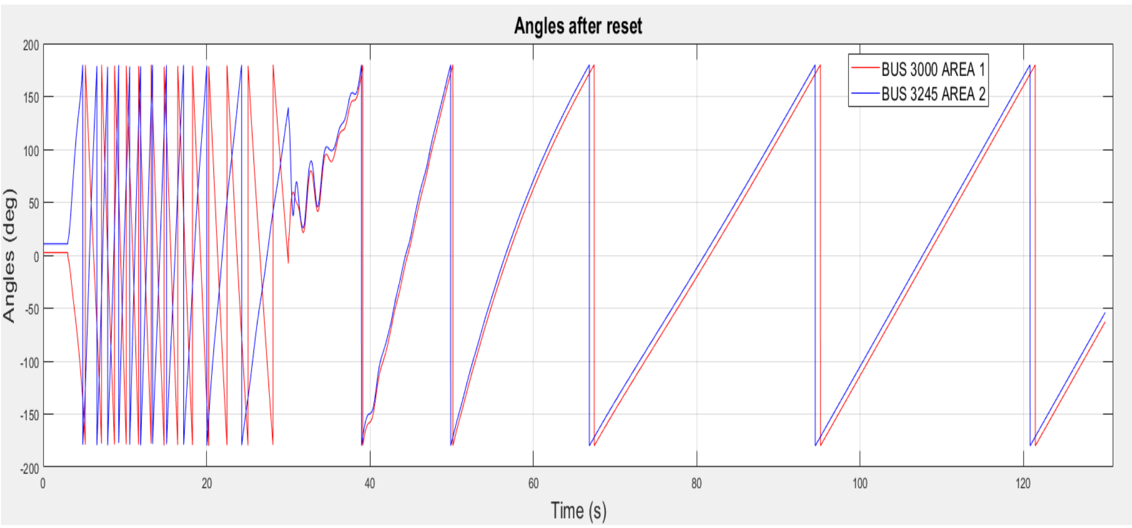

Figure 4.6: Bus angles after reset method

From the figures above, the first section of the graphs describes the oscillations also referred as "power swings" that are created by the generators when the disturbance occurs, since the phase angle of the buses depends on the combination of the generators present in that particular bus. The inertia of the rotating generators causes

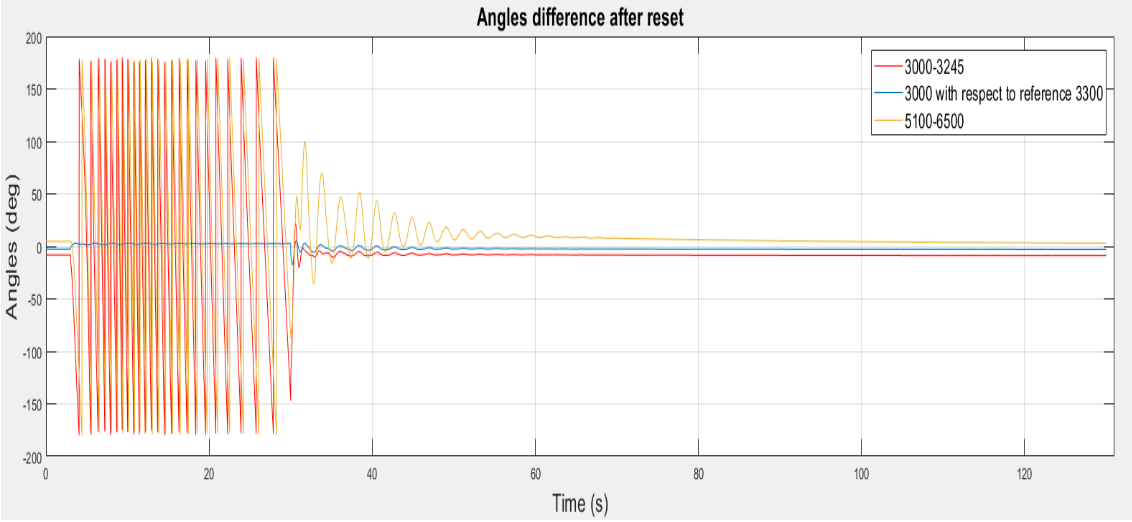

Figure 4.7: Bus angles difference where (1) red line shows angle diff. between bus 3000(SE3) & 3245(SE2), (2) blue line displays the angle diff. between bus 3000 & reference bus 3300 in SE3, (3) yellow line shows the angle diff. between bus 5100(NO6) & 6500(NO7)

the continuation of these oscillations until it reaches a new steady state. During reconnection of the lines, the tuning that was made assisted in synchronizing the angles together in a coordinated manner seen by the response of the angle plots in both figures. This stabilization of the angle difference denotes that there is no change in the relative positions of the generators in the two subsystems. Hence the angle difference between the subsystems reaches a new steady operating point and maintaining a constant phase difference relationship. Therefore implies that the power exchange has reached a balanced state.

4.2.3 Power Exchanges

Before the split, the power exchange between the predefined subsystems are described by the flow from area 2 to area 1. It is logical since the area which experienced a deficit in power is area 1, while vice versa with area 2. The power flow through the branches for the buses that run along the line of split was calculated for both areas. For the power exchange between Area 2 to Area 1, it was found that area 2 was providing area 1 with **1573.7 MW** of power. This is understandable since 8 tripped lines were located in Sweden, connecting SE2 to SE3. In addition to hydropower generation in central and northern Sweden (SE1 & SE2) as the main source and wind power located in central Sweden (SE2) which has seen to be rapidly expanding. The ninth transmission line that was tripped is located in Norway, with a low power flow of -87.5 MW from area 2 to area 1, which is considered low compared to the power flow through the lines located in Sweden. While the power exchange between Area 1 to Area 2, the power flow was calculated as **-1543.2 MW**. The small difference is normal due to losses that occur during the transmission process.

At the moment where the disturbance was initiated, the large interconnected power system had split into two subsystems and the power exchange between the two synchronous areas had come to zero. At the time of the simultaneous reconnection, the power flow dynamics experienced a momentary surge of power in all lines due to the effect of reconnecting of the lines although was not a cause for concern. This surge can be defined by several factors such as (1) phase angle differences between the subsystems at the moment of the reconnection, (2) the system response to the mismatch of reactive power flows to stabilize the voltage levels and (3) the transient oscillations of the transmission lines at the moment of reconnection due to sudden current flow through the lines. Soon after, the power flow between the two areas stabilized,and the power exchange between the areas had returned into its normal operating condition. Figure 4.8 and 4.9 below depicts the active and reactive power flow respectively between the two branches connecting bus 3000 in (SE1) and 3245 in (SE2) together.

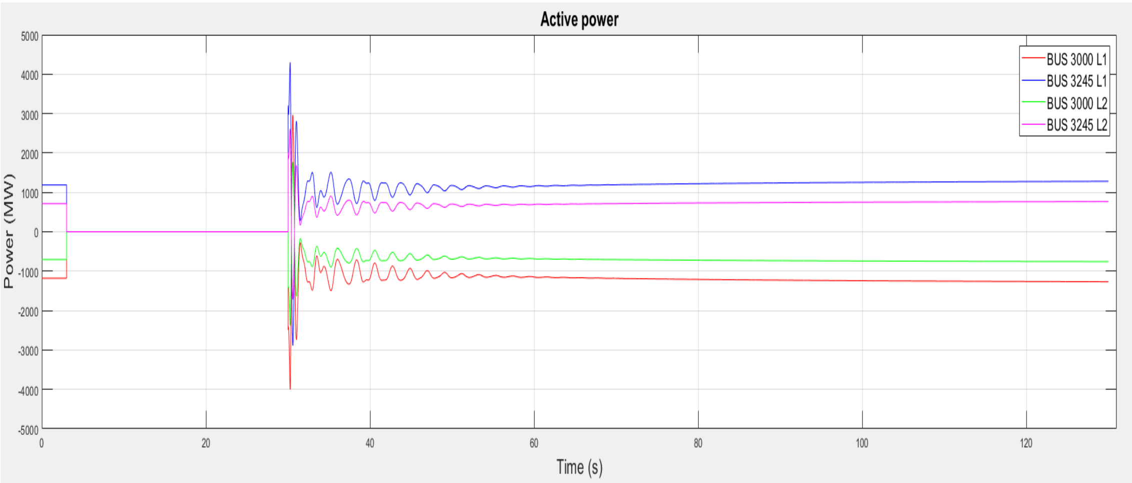

Figure 4.8: Active Power flow at the two transmission lines connecting buses 3000 & 3245

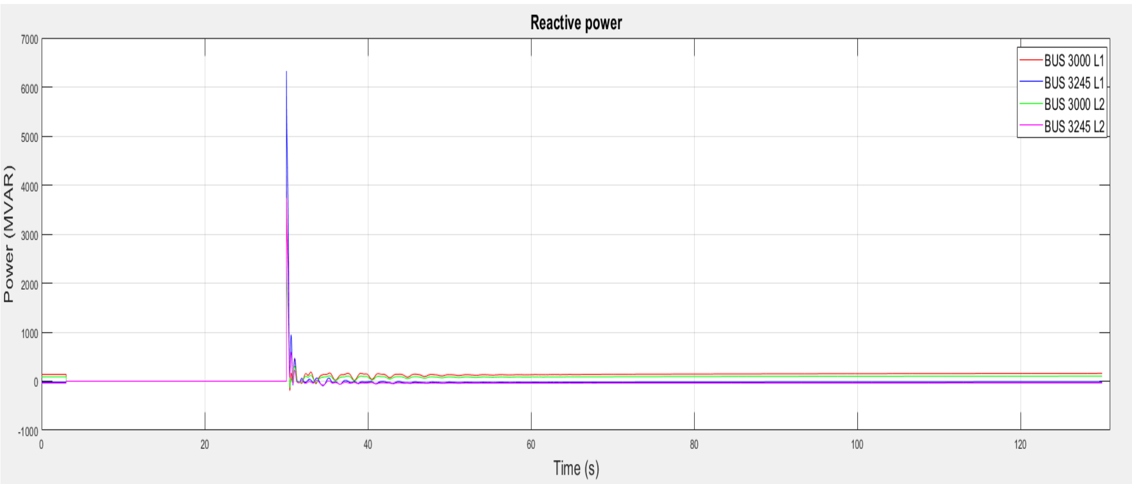

Figure 4.9: Reactive Power flow at the two transmission lines connecting buses 3000 & 3245

4.3 Sequential Resynchronization

This approach points out the reconnection method used by TSOs in today's power systems in case of a disturbance occurrence. It utilizes the available resources for the prevention against any event that could danger the stability and operation of the power system.

Since this resynchronization method requires the successive return of the tripped lines in the power system one at a time. To determine the time between each reconnection, the system's frequency, voltage levels should be within acceptable limits depending on the synchronizer device settings, the need for the transient oscillations to be damped before commencing the reconnection. After communications are made between TSOs. the decision for reconnecting the lines is carefully made. Two branches connecting bus 3000 in SE3 with bus 3245 in SE2 along the split line are monitored for the synchronization attempt of the two subsystems, branch with ID 1 will be the first line to be restored since it is considered to have the strongest power link amongst the other transmission lines. Table defines the order of the reconnection of the tripped lines according to how strong their power link in the power system.

Table 4.1: Reconnection order of Transmission Lines

Buses (From-To)	Region	Lines	Reconnection order
3000-3245	SE3–SE2	Line 1	1st
	SE3–SE2	Line 2	2nd
3100-3359	SE3–SE2	Line 2	3rd
	SE3–SE2	Line 1	4th
3000-3115	SE3–SE1	Line 1	5th
5100-6500	NO6–NO7	Line 1	6th
3100-3200	SE3–SE2	Line 1	7th
	SE3–SE2	Line 2	8th
	SE3–SE2	Line 3	9th

4.3.1 Voltage & Frequency profiles

Figure 4.10 and 4.11 below displays the voltage and frequency variations over time between the two buses where the first reconnection took place. Initially, same as the figures plotted during the simultaneous reconnetion, due to the disturbance there were significant discrepancies in the frequency levels, however the voltage levels have demonstrated slight oscillations. Moreover the response of the system to this type of reconnection is different than the previous method used.

At the time of the reconnection, it can noticed from the line at which the first reconnection was made that the frequency could not align properly. A decrease in the frequency was noted in both subsystems which clearly implicates the ineffectiveness of the reconnection. Following the disturbance, the two subsystems operating with different frequencies and during the first reconnection attempt, the sudden power exchange created a transient causing a temporary frequency drop. Due to the frequency deviations and the transient power flow oscillations and instability on the system were created and could not immediately stabilize until the second reconnection attempt. At the 40 second mark, where the second attempt for reconnection was made, the two subsystem frequencies started to align together and the oscillations in the frequency started to damp until it stabilizes. While the voltage between the buses in figure 4.10, although both subsystems voltage seem to damp after the first reconnection, however at the second attempt the fluctuations seem to persist even after the third reconnection at 50 second mark. Eventually the system seems to stabilize and both subsystems synchronize.

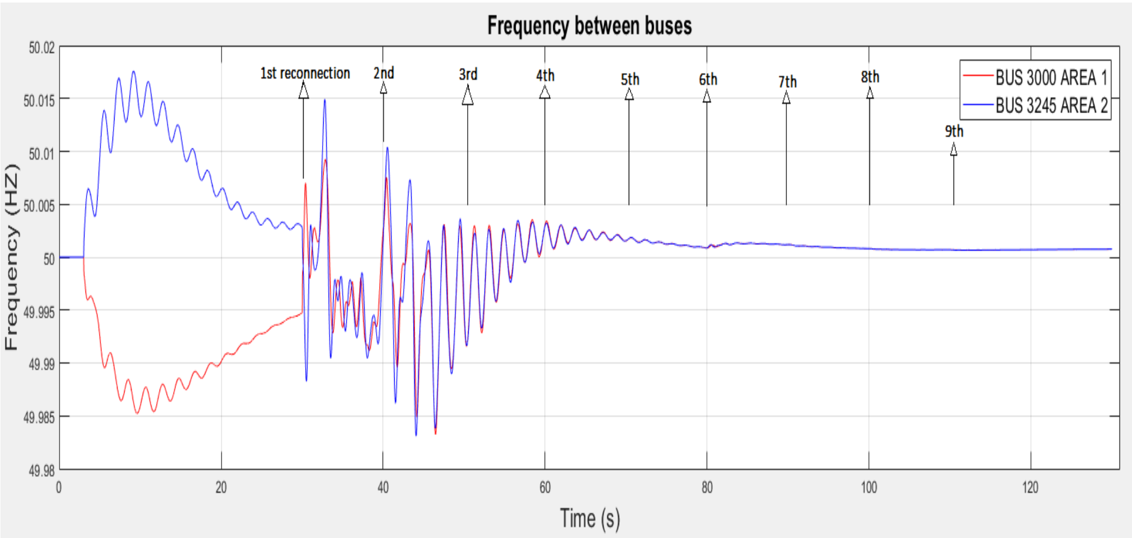

Figure 4.10: Frequency recordings of buses 3000 in SE3 & 3245 in SE2

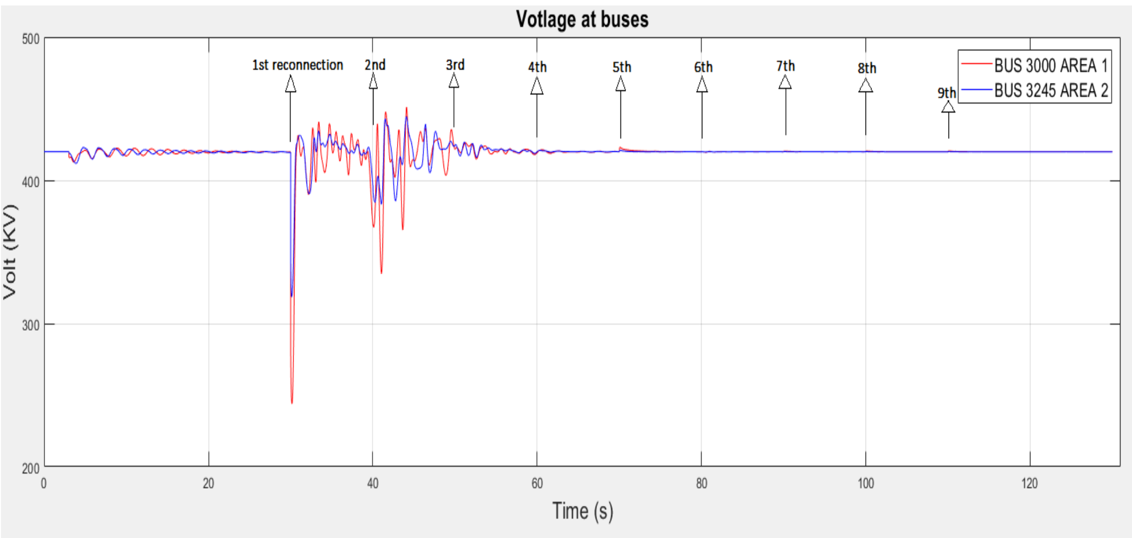

Figure 4.11: Voltage recordings of buses 3000 in SE3 & 3245 in SE2

Figures 4.12 and 4.13 depicts the frequency and voltage recordings of buses 3359 located in area 1 and 3100 located in area 2 where the third and fourth reconnection of the lines was executed. It can be seen from figure 4.12, bus 3100 exhibited a voltage dip at the time of the disturbance occurrence, this is due to the fact of absence of a generator located in the bus as the power fed to the bus only provided for the load in the bus. At the instant of reconnection, both buses experience oscillations in the frequency and voltage at 60 second marker. The voltage at bus 3100 stabilizes but not to its initial value, moreover when the 7th, 8th and 9th reconnection was made, its value returned in steps.

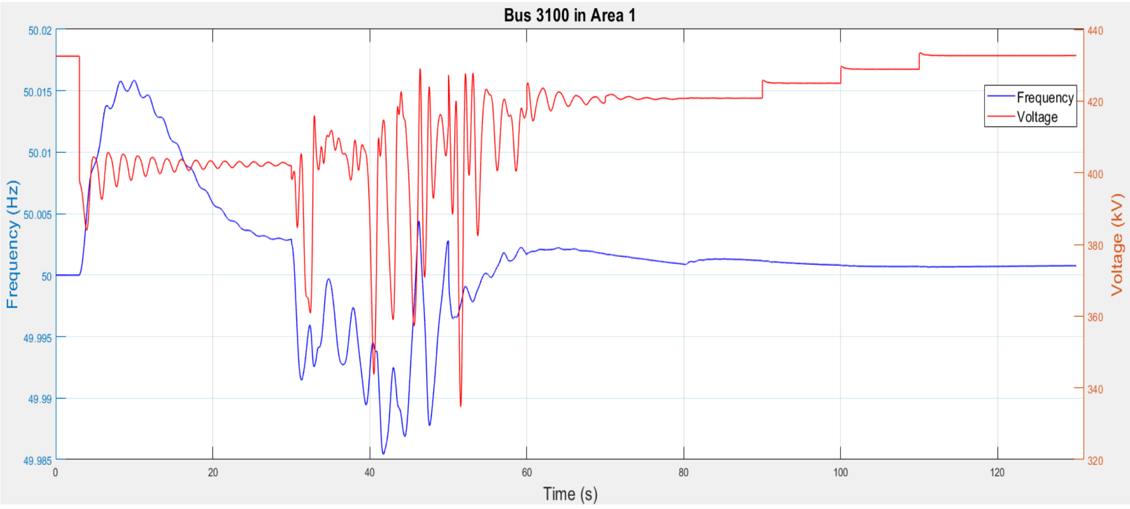

Figure 4.12: Voltage & Frequency recordings of Bus 3100 in SE2

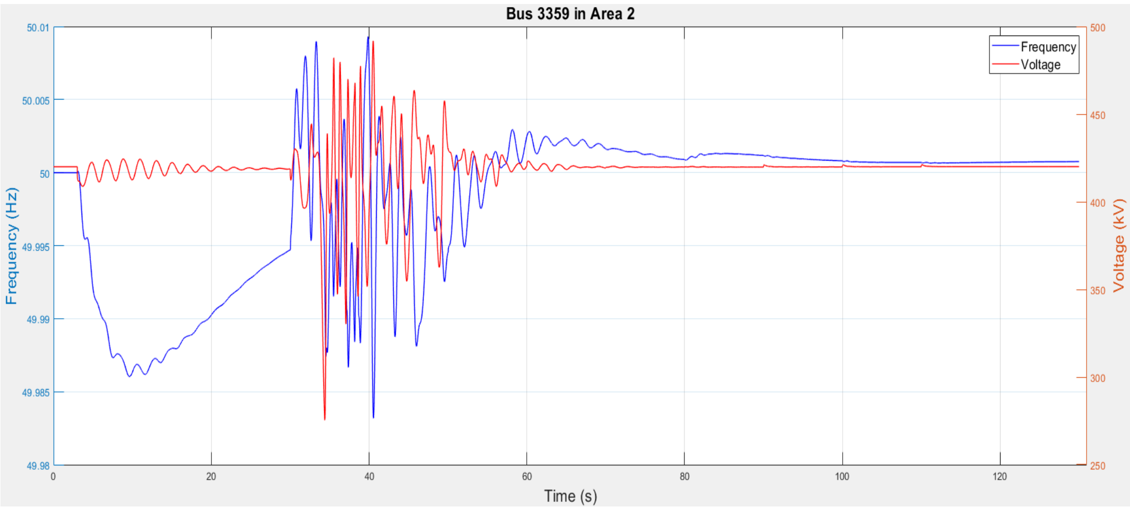

Figure 4.13: Voltage & Frequency recordings of Bus 3359 in SE3

4.3.2 Phase angle

Same procedures as in the simultaneous method were made for the phase angle between the two subsystems. Figure 4.14 depicts the angles at buses 3000 and 3245 after the reset method has been implemented, while figure 4.15 displays the angle differnece between the two buses, in addition to the angle differnce between the reference bus 3300 and between bus 5100 and 6500 located in Norway.

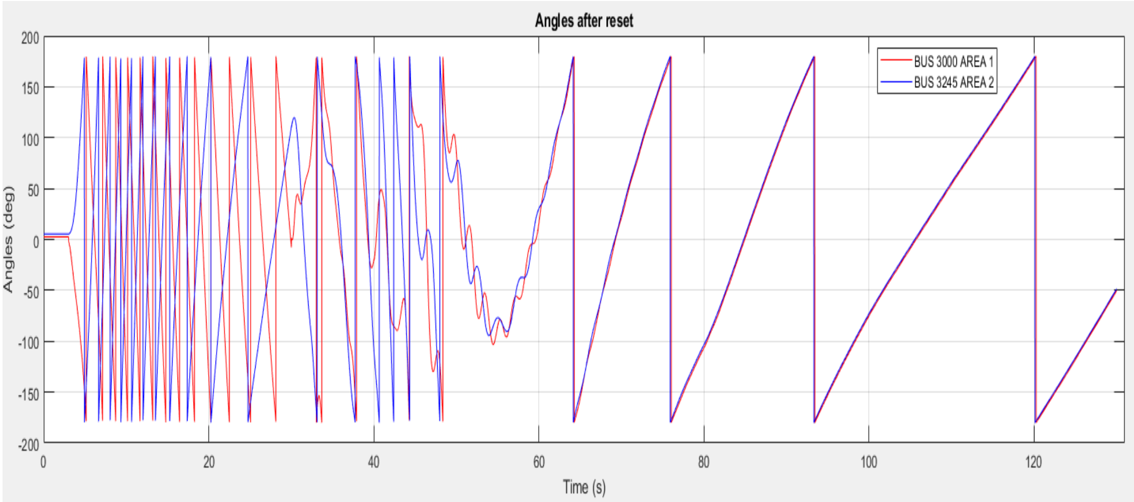

Figure 4.14: Bus angles after reset method between bus 3000 in SE3 & 3245 in SE2

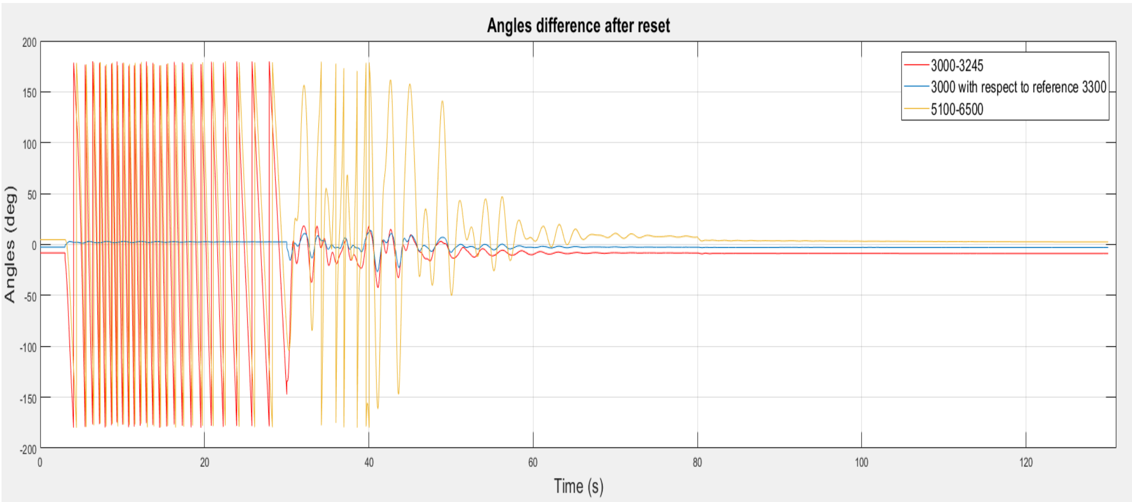

Figure 4.15: Bus angle differences between (1) bus 3000(SE3) & 3245(SE2) depicted by red line, (2) blue line displays between bus 3000 & reference bus 3300 in SE3, (3) bus 5100(NO6) & 6500(NO7) showed by yellow line

From the point at which the disturbance occurred, the angles experience the same fluctuations as in the previous method. A drastic change is noticed at the instant of the reconnection (i.e. 30 second mark), both of the angles in figure 4.14 exhibit variable changes, due to the fact that the line could not withstand the huge flow of power. At the 50 second mark, after the second reconnection attempt and the connection of three additional lines, the system starts to stabilize and the alignment of the angles becomes inevitable. As can be seen from figure 4.15 the angle difference of the buses are always having different values, which can be noticed clearly from the differences between bus 5100 and 6500 in Norway. A minute into the simulation, the angle difference seems to reduce and stabilize to a small value indicating the resynchronization of the two subsystems.

4.3.3 Power flow

The power exchange at the time of the disturbance between the subsystems was zero. The power flow during the sequential reconnection underwent variations from the point of the first reconnection to the last reconnection made. This is a result of the reconnection of the lines one at a time. Figure 4.16 and 4.17 depicts the active and reactive power flow at the branches where the first, second reconnection occurred. Since the buses contain two and parallel lines, for figure 4.16 the first reconnection occurred on line 2 of the buses while the second reconnection on line 1. As for figure 4.17, depicts the reactive power.

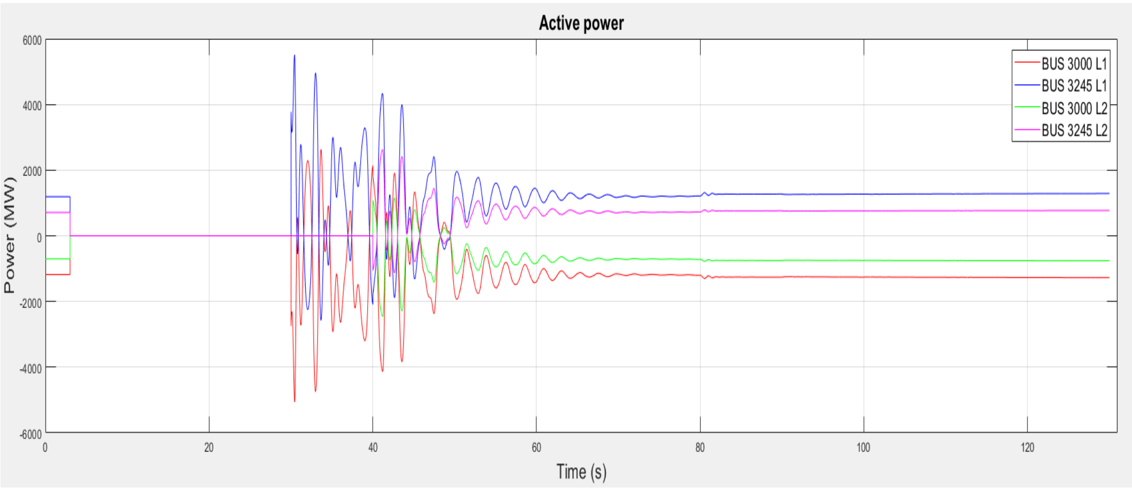

Figure 4.16: Active Power exchange for 1st and 2nd reconnection

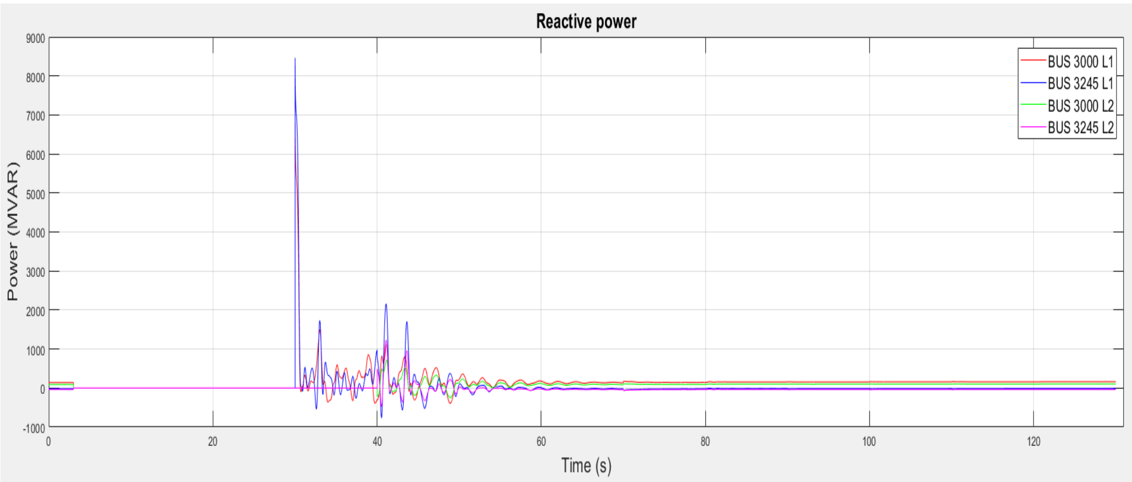

Figure 4.17: Reactive Power exchange for 1st and 2nd reconnection

It can be noted how the power started to flow at the point when the reconnection was made, The difference between the first and second reconnection attempt is that the huge surge of power is very large for the line to withstand alone, until the second attempt where the other reconnection was made that the surge of power started to decrease gradually until it reached the normal value at which the power was flowing.

4.4 Sequential Delay

A sequential delay is a time delay introduced between each line of the reconnection step when trying to resynchronize the subsystems together. The timing of these reconnections has to be carefully monitored and smoothly executed by the system operators to ensure successful reconnection. A 20 second delay was introduced between the first and the second reconnection of the lines since the first reconnection establishes the initial power flow between the subsystems and the second reconnection reinforces the first by providing an additional path for the power to flow. This delay was made to showcase the ineffectiveness of this method to balance the power and stablize the voltage of the subsystems during the reconnections. The remaining lines had a 10 second interval between each reconnection step. Figure 4.18 below displays the frequency recordings between the two buses where the first reconnection occurred.

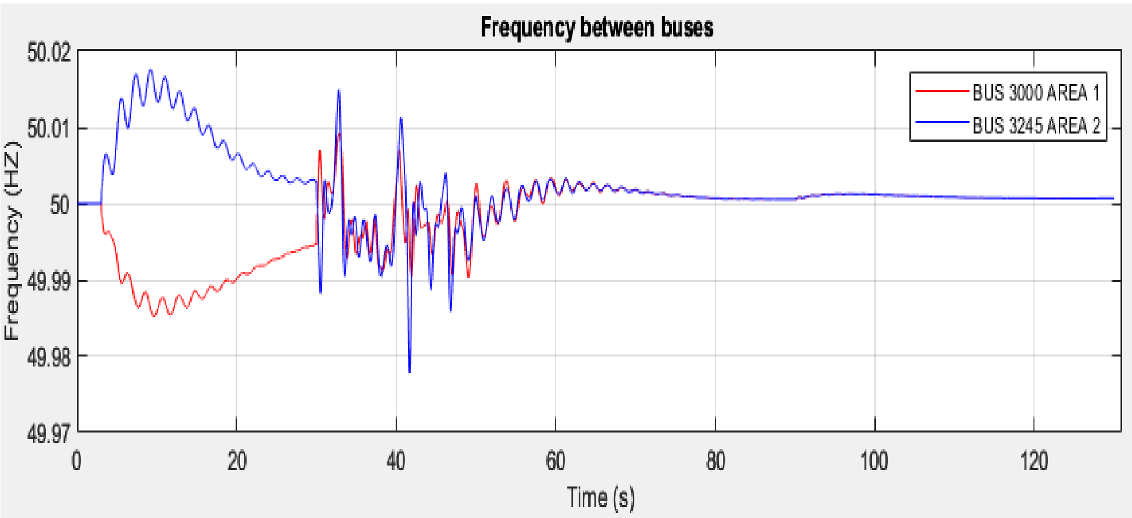

Figure 4.18: Frequency recordings of buses 3000 & 3245

As can be noticed from the figure above the frequency matches that of when the interval between the first and second reconnection was 10 seconds. However, the importance of the delay heavily impacted the subsystems ability for power balance and obstructed its ability to stabilize which caused and prolonged the frequency deviations after the 40 second mark, hence extended the instability of the subsystems due to these oscillations in the frequency.

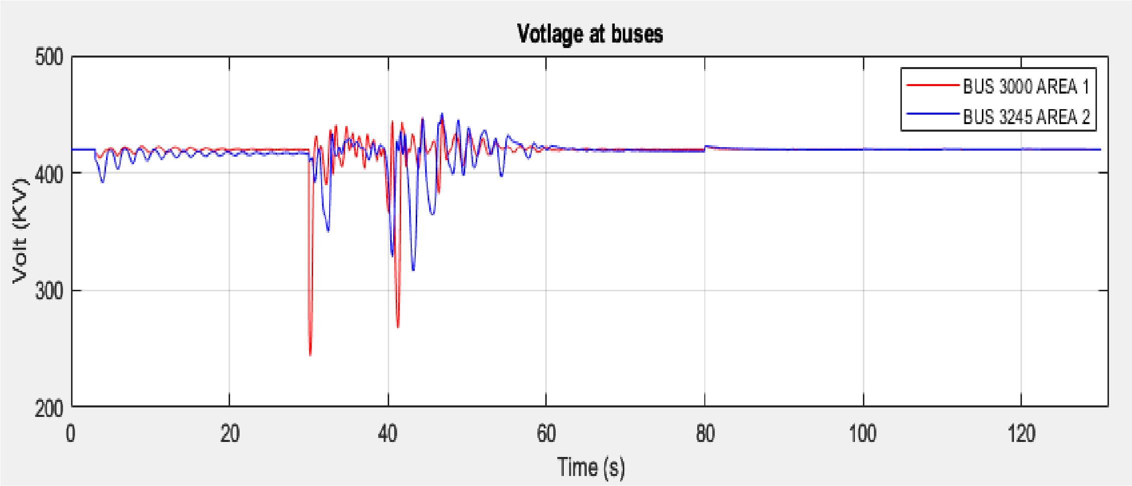

Figure 4.19: Voltage recordings of buses 3000 in SE3 & 3245 in SE2

Figure 4.19 displays the voltage recordings between the buses where the first reconnetion of the line occurred. Although it looks similar to the first simulated 10 second interval but it seem to exhibit a secondary voltage dip after the first reconnection attempt in bus 3000 located in area 1. Once again, it resulted in a failed attempt to resynchronize the subsystems.

Figure 4.20 and 4.21 below depicts the angles and angle difference between the buses after the reset method has been applied. It can be noticed the oscillations in the angles does not seem to stabilize until after the 60 second mark.

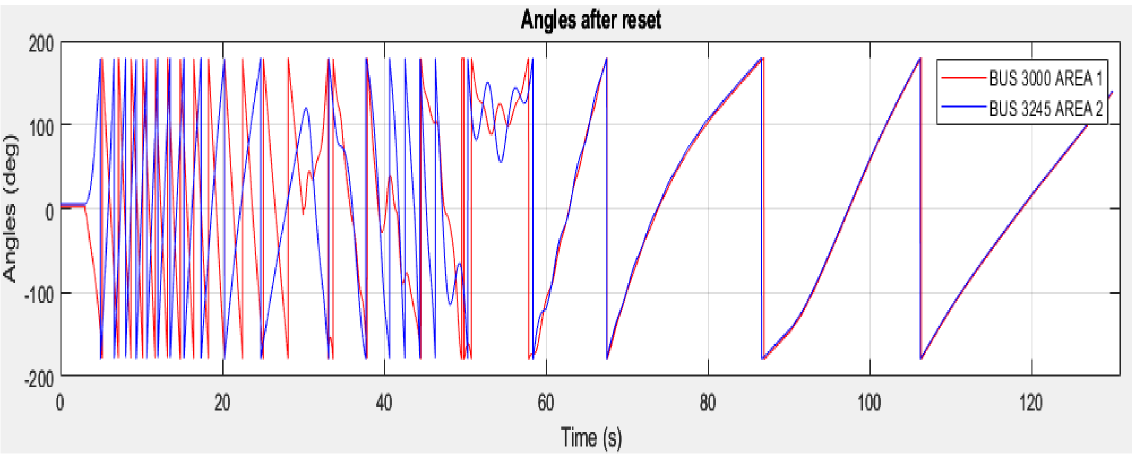

Figure 4.20: Bus angles after reset method between bus 3000 in SE3 & 3245 in SE2

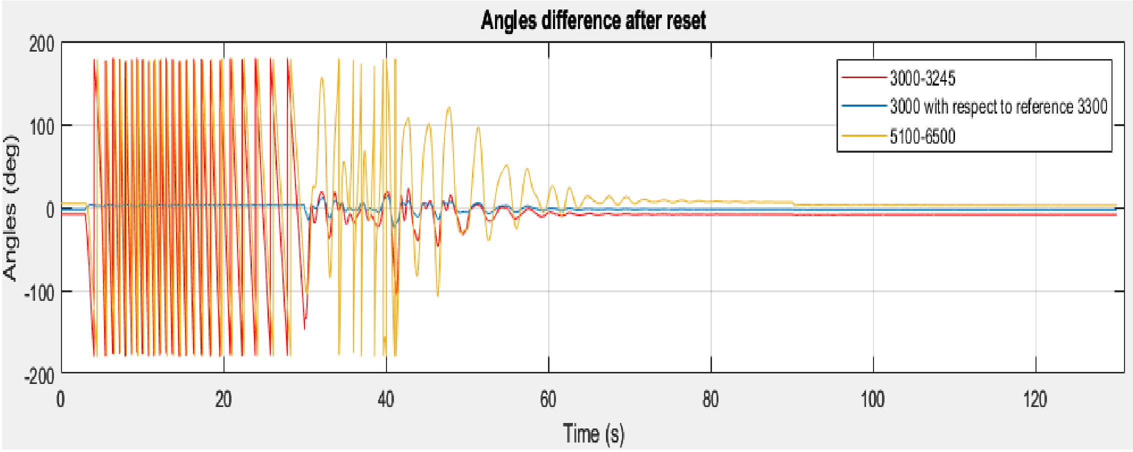

Figure 4.21: Bus angles difference Bus angle differences between (1) bus 3000(SE3) & 3245(SE2) depicted by red line, (2) blue line displays between bus 3000 & reference bus 3300 in SE3, (3) bus 5100(NO6) & 6500(NO7) showed by yellow line

4.5 Synchronizer Settings

To assess the applicability of these devices based on the obtained results, the synchronizers along with their recommended data and parameter settings were studied and compared to the simulation results. The technical data for the two synchronizers are provided below:

4.5.1 SYNCHROTACT 6

The followings settings are essential for safe and efficient synchronization process, ensuring stable power system operation. The flexibility in the parameter ranges enables system operators to adjust the settings based on specific conditions and requirements needed during the process.

- **Voltage Settings:**
  Knowing the voltage settings for synchronizing a generator to the grid using the SYNCHROTACT 6 device is critical to ensure that the voltage levels of the generator and the grid are closely matched. The recommended maximum voltage difference between the generator and the grid should be set within 5% to 40% of the nominal voltage[49]. This setting allows for flexibility depending on the specific conditions of the synchronization process. For dead bus conditions, where the bus voltage is zero, the maximum voltage should be set between 0% and 50% of the nominal voltage [49].

- **Frequency Settings:**
  Frequency synchronization is essential to prevent any transient oscillations and ensure smooth matching of the generator with the grid. The nominal frequency for the device is set to accommodate a range of common grid fre-

quencies, including 50 Hz and 60 Hz[49], with an operational frequency range from 10 Hz to 100 Hz [49]. The slip limit, which indicates the allowable difference in frequency between the generator and the grid, should be set between 0.1% and 2% [49]. This range ensures that the generator frequency is closely matched to the grid frequency before the synchronization process is attempted.

- **Phase Angle Settings:**
  The phase angle difference between the generator and the grid must be minimized to ensure a stable connection without causing power surges or equipment damage. The SYNCHROTACT 6 device allows the phase angle limit to be set between 5 degrees and 40 degrees[49]. This parameter setting ensures that the generator is in phase with the grid before closing the circuit breaker, reducing the risk of synchronization transients[49]. The device also includes features to monitor and adjust the phase angle continuously during the synchronization process to maintain optimal conditions[49].

4.5.2 SIPROTEC 7VE85

By adhering to these recommended settings for voltage, frequency, and phase angles, operators can achieve reliable and efficient grid synchronization, ensuring the stability and reliability of interconnected power systems.

- **Voltage Settings for Synchronization:**
  The device allows for precise control and synchronization of generators to the grid by closely monitoring voltage parameters[50]. For effective synchronization, the reference voltage (V1) and the voltage to be synchronized (V2) must be carefully managed. Both V1 and V2 are measured as phase-to-phase voltages and their recommended range is from 10% to 120% of the rated voltage (Vrated)[50]. This broad range ensures that the synchronization process can accommodate various operational conditions. The tolerance for these voltage measurements at the rated frequency is within 1% of the measured value or 0.5% of Vrated[50], ensuring high accuracy. Additionally, the permissible voltage difference between the two systems (V1 - V2) should also fall within this range[50], maintaining a similar tolerance, which is crucial for preventing voltage imbalances during synchronization.

- **Frequency Settings:**
  Frequency synchronization is another aspect managed by the device. It ensures that the frequencies of both the reference voltage (f1) and the voltage to be synchronized (f2) fall within a specified range[50]. This range is from 25 Hz to 70 Hz[50], accommodating the standard operating frequencies of most power systems. The tolerance at the rated frequency is set to 1 mHz[50], allowing for precise frequency matching. The acceptable frequency difference between the two systems (f1 - f2) is also defined within this range, with the recommended setting being ± 10% of the rated frequency[50]. Maintaining this frequency difference within tight tolerances is essential for minimizing transient oscilla-

tions and ensuring smooth synchronization.

- **Phase Angle Settings:**
  Phase angle difference is another crucial parameter for synchronization, and the SIPROTEC 7VE85 device allows for accurate monitoring and adjustment. The phase angle difference between the two voltages ($\theta_1 - \theta_2$) is measured in degrees, with a recommended range from -180° to +180°[50]. This wide range ensures that synchronization can occur under various phase conditions. The tolerance for the phase angle at the rated frequency is set to 0.5°[50], providing the precision necessary to align the generator's phase with the grid phase accurately. This precise phase matching helps in avoiding synchronization transients that could destabilize the power system[50].

- **Additional Parameter Settings:**
  In addition to voltage, frequency, and phase angle settings, the device allows for setting other parameters to fine-tune the synchronization process[50]. These include maximum differential values for voltage difference, frequency difference, and angle difference, with default settings at 2.0 V, 0.10 Hz, and 10°, respectively[50]. The operating voltage range is specified from 20 V to 340 V, and the frequency range of ± 4 Hz of the rated frequency[50]. Tolerances for these settings are 2% of the pickup value or 1 V for voltage, 10 mHz for frequency difference, and 1° for angle difference[50]. These additional settings and tolerances ensure that the synchronization process is not only accurate but also adaptable to different operational scenarios, thereby enhancing the reliability and stability of the power system[50].

Table 4.2 below sums up the data of the synchronizer devices mentioned above and their recommended settings for successful resynchronization of the generators to the grid.

Table 4.2: Comparison of Synchronizer Settings

Parameter	SYNCHROTACT 6	SIPROTEC 7VE85
Voltage Settings	- Max difference: 5% - 40% - Dead bus: 0% - 50%	- V1, V2: 10% - 120% Vrated - Tolerance: ±1% (V1-V2)
Frequency Settings	- Nominal: 50/60 Hz - Range: 10 - 100 Hz - Slip: 0.1% - 2%	- Range: 25 - 70 Hz - Tolerance: ±1 mHz - Difference: ±10% Vrated
Phase Angle Settings	- Limit: 5° - 40° - Continuous adjustment	- Range: -180° to +180° - Tolerance: ±0.5°
Additional Settings	N/A	- Voltage: 2.0 V - Frequency: 0.10 Hz - Angle: 10° - Operating: 20 V - 340 V - Frequency: ±4 Hz - Tolerances: ±2% or 1 V ±10 mHz ±1°

4.6 Analysis & Comparison of Results

The above results showed the effectiveness of the two reconnection methods used to resynchronize two subsystems into which was initially a large interconnected Nordic power system after experiencing a disturbance. It also highlighted differences between the two methods having different outputs and rates of success. The simultaneous reconnection had resulted in a success from the first attempt while the contrary with the sequential reconnection as the first attempt had failed.

It can be seen that the rate at which the frequency falls or increases for both subsystems after the disturbance is determined by the magnitude of the power deficit/surplus, which in this case is considered having a small value of (i.e.$\pm$0.016 Hz) from the nominal 50 Hz frequency, in comparison to real life events. It should be noted that without altering the initial conditions of the model, the disturbance would not have been created. A larger power imbalance would mean larger deviations in the frequency of both subsystems, hence larger frequency differences than those in the simulation results. However due to the network topology, only limited altering was made to ensure the whole model would react as if it was in normal operation.

For both cases at the time of the disturbance, individual TSOs had initiated automatic defense measures such as frequency containment reserves (FCR) and load shedding, etc., which were activated momentarily when frequency deviations were noticed. These measures prevented excessive damage such as blackouts. The participation of such measures helped in maintaining the frequency of both areas from increasing or decreasing above or below certain limits. This stabilization was crucial in maintaining system integrity until the reconnection methods were put to place.

The simultaneous reconnection's success was based on the deployment of the PMUs on all buses. The coverage of the whole system allowed for immediate identification of the disturbance location, enabling TSOs to quickly gather and analyze data from the entire network and pinpoint the necessary mitigation plans, hence enabling the immediate reconnection of the lines and restoring the system operation. On the other hand with sequential reconnection, the placement of PMUs on specific buses was helpful however was limited, this caused delays in not only the exchange of the necessary data but also obstructed the coordination between TSOs of the entire network and confirming the synchronization at its early stage. This eventually resulted in the failure of the reconnection from the first attempt.

Additionally to include to the point mentioned above, the use of the simultaneous reconnection method achieved faster resynchronization. PMU deployment allowed TSOs to get a comprehensive data outlook to address all the disconnected lines simultaneously. This paved the way for swiftly activating the necessary resources while minimizing the duration of the system where it had experienced a power imbalance. This ensured that the power system remains reliable and lessened the impact of the disturbance. However with the sequential reconnection, each reconnection attempt presents a potential risk of failure that eventually prolonged the instability of the system which could increase the risk for additional disturbances.

The success of the simultaneous reconnection method over the sequential method is evidently shown in the minimizing angle difference between the two subsystems. By reconnecting all the lines at once, the approach eliminates the prolonged process reducing the risk of further misalignment and phase angle differences. The placement of PMUs across the network enabled TSOs to swiftly identify the right moment for resynchronizaton and avoided any unnecessary deviations, returning the system to its initial operational condition and enhanced the overall stability.

Another point to discuss is that the introduction of the sequential delay between the first and second reconnection had contributed to the failure of the sequential resynchronization. The delay extended the overall time of the method which increased the strain on the network elements. In addition, extra continuous monitoring and coordination between TSOs is needed before other complications occur and furthermore makes the resynchronization process harder. Ultimately, the effect of the delay resulted in the inability of the system to keep stability that led to failure of the method.

Furthermore, the use of the synchronizers which are utilized to match and synchronize the generators of both subsystems together at the instant of resynchronization. It is noticed with the simultaneous reconnection, although it needed a highly coordinated approach but the use of PMUs allowed the synchronizers with real-time data enabling rapid adjustments to be made when necessary to ensure the entire system is synchronized from the first attempt. As for sequential reconnection, although the use of the synchronizers was essential but was not of a positive result. The main reason is the delay of information which made the job for the TSOs and the synchronizers hard and time consuming. Continuous monitoring and exchange of information is necessary as not let anything interfere when its time for the reconnection. Moreover, the necessity of ensuring system stability at each reconnection attempt before proceeding to the next which increases he complexity of the overall operation.

Lastly, it is important to note that while the tuning settings employed in the resynchronization methods discussed are specifically accustomed to the Nordic model, these settings maybe not be applicable to other power system models. Different models have varying characteristics, network topologies and specific operational conditions such as load, generation and network impedances at different locations, that may require extra adjustments to be needed accordingly. This method serves as a foundation that can be adapted and tuned across different power system configurations and scenarios and its practicality in resynchronization efforts done by TSOs worldwide.

4.7 Sustainability & Ethical Aspects

An important ethical discussion relevant to this thesis project defined by the IEEE ethical code of conduct, is the adherence to the principles of equality and respect.

Honest criticism of the technical work was given and accepted throughout the meetings with the supervisor and the examiner. This is useful for acknowledging the correction of errors based on the available data and the credit to be given to the contributions of others. It became significant to appreciate comments and suggestions according to everyone's expertise. This approach guaranteed the thoughts of the individual whether it was the student, supervisor or examiner, to be acknowledged and given/taken with consideration, even when the time was limited.

Additionally, as an individual partaking in this project who had developed a deeper understanding of the conventional and emerging technologies, Nordic44 power system model and the power system simulation using PSS/E with the aid of python, that had impacted the course of the study in many ways. A realistic approach was developed of how system operators think and how decisions were made in response to any event that would risk the power system stability and integrity.

Furthermore, another important ethical code of conduct is ensuring fair treatment of all individuals, avoiding any form of discrimination based of factors like race, religion, gender, age, disability or national origin. Despite the different backgrounds and age differences, the chance to prefer the supervisor comments over the examiner and vice-versa was possible, but the principles of equality was adhered to and each valuable comment and suggestion without regard to specific competence was taken very seriously.

From a sustainability point of view, the methods developed and tested such as simultaneous resynchronization using PMUs, contribute to maintaining the stability of the grid. Stability of grids are of the essence when it comes to the integration of renewable energy sources, which are variable and can introduce instability. Additionally, load shedding is often necessary during disturbances, with the improved resynchronization processes the need for load shedding is reduced. This leads to an efficient energy use and less wastage benefiting to the environmental goals. Moreover,the use of WAMS and PMUs allows for better monitoring and control of the grid when integrating the renewable energy sources with variable outputs. This in turn, positively impacts the environment by utilizing the use of clean energy and reducing energy losses.

5

Conclusions & Future Recommendations

The chapter summarizes the key findings of this thesis, highlighting the implications of the research. Additionally, it outlines new pathways for future work by providing recommendations to improve the current study and advancing in the field.

5.1 Conclusion

The comprehensive analysis of sequential and simultaneous methods for reconnecting two synchronous areas shows the clear advantage of simultaneous reconnection. The method's success from the first reconnection attempt showcases its efficiency and reliability. The deployment of PMUs across all buses is utilized providing real-time data which enables TSOs to detect and identify the disturbance's location and type, hence responding as fast as possible. Additionally, the total time required for synchronization of the subsystems is reduced drastically by addressing all disconnected lines at once, minimizing the system downtime and the the risk of further instability and blackouts. The combined and rapid response of the automatic response measures and TSOs facilitated by this method ensures a more stable and smooth resynchronization process, moreover maintaining the integrity and operation of the power system.

In contrast, the sequential reconnection method faced with many challenges that proves the simultaneous reconnection method effectiveness more. Some of the challenges that were faced such as, delays are introduced at every step there is a need to reconnect the lines one at a time, in addition to the constant communication and communication needed by TSOs. Each reconnection attempt presents a potential point of failure, that increases the risk of intervening disturbances and proposes repeated involvement of extra procedures to be made. This prolonged process endangers the system condition to maintain its stability while also straining the available resources, resulting in economic losses and operational disruptions. The sequential reconnection method being a step-by-step method, increases complexity and downtime for the power system seen by the fail of the reconnection attempt in the simulation conducted.

The adaptability of the simultaneous method in resynchronization strategy in combination with speed and efficiency enables it to operate on different power system models. This makes it a superior cchoice for resynchronizing power system after disturbances, as was showcased by the simulations of its successful performance in the reconnection.

5.2 Future Recommendations

Based on the conclusion that has been made, some further investigations can be stipulated from the thesis to more enhance the capability of this method to be functionally operative on future power systems. These future recommendations are listed below:

- **Rotor angle studies:**
  Rotor angle stability is considered an important role for any power system stability. The trasnient stability of the rotor angle is the ability of the system to keep synchronism in the event of a disturbance [51, 52]. Significant changes start to appear in the generator's rotor angle, hence introducing changes in the power flow. Keeping the rotor angle within certain limits maintains synchronism and system operation[51, 52]. Therefore, as a future recommendation, rotor angle studies should be conducted to further analyze its impact and role on the power system.

- **Cost of PMUs:**
  Due to the expensive cost of the whole operation (i.e. materials, installation, maintenance and communication infrastructures) of PMU sensors, the number of required sensors and measuring devices in the network should be optimized to make full observations while being cost-effective[53]. Studies should be conducted on the relationship between the cost of the PMU sensors with regard to the placement and number of PMUs located in the network.

- **Phase-Locked Loop system (PLL):**
  PLL is mostly used as a synchronization mechanism for the integration of wind energy and other renewable sources into the grid. It ensures the power injected by renewable energy systems (RES) are within the grid's voltage, frequency and phase angle magnitudes, to ensure the grid stability[54]. PLL is primarily used to synchronize the generator's output with the grid by locking the frequency and phase, while have recently been used in conjunction with WAMS[54]. As a further study, the application of PLL in WAMS can be conducted resulting in a deeper understanding.

- **System Synchronization using Synchronizers:**
  Since the synchronizer devices are used to sync the generator by matching the voltage, frequency and phase angles with the power grid . A study to investigate the functionality of these synchronizers when used for whole system resynchronization and what effects does it have on the generators of the power system as a whole in contrast to only one generator.

- **Internet of Things (IOT):**
  IOT refers to a user friendly network of physical objects embedded with sensors, softwares and other technologies solely for the purpose of exchanging data with other devices and systems over the internet[61]. Future studies about IOT platforms for WAMS systems should be carried out. The use of IOT especially with the deployment of PMUs, enables for a smarter more connected environment. This allows for TSOs to view and reflect on the status of the power system, which enables easier detection and mitigation of any event that occurs.

- **Cloud Sharing:**
  One disadvantage of PMUs is the large volume of data collected at each bus or substation. This results in limited storage capacity and makes the data communication between TSOs very challenging[56]. One solution which can be further studied and implemented in this research is, a secure and reliable IOT platform designed for data processing known as clouds[56]. Cloud sharing between IOT devices located in different locations of the network enables TSOs to receive and send data immediately without any communication delay between the parties. This ensures faster detection and response time to any type of event[56].

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A

Appendix 1

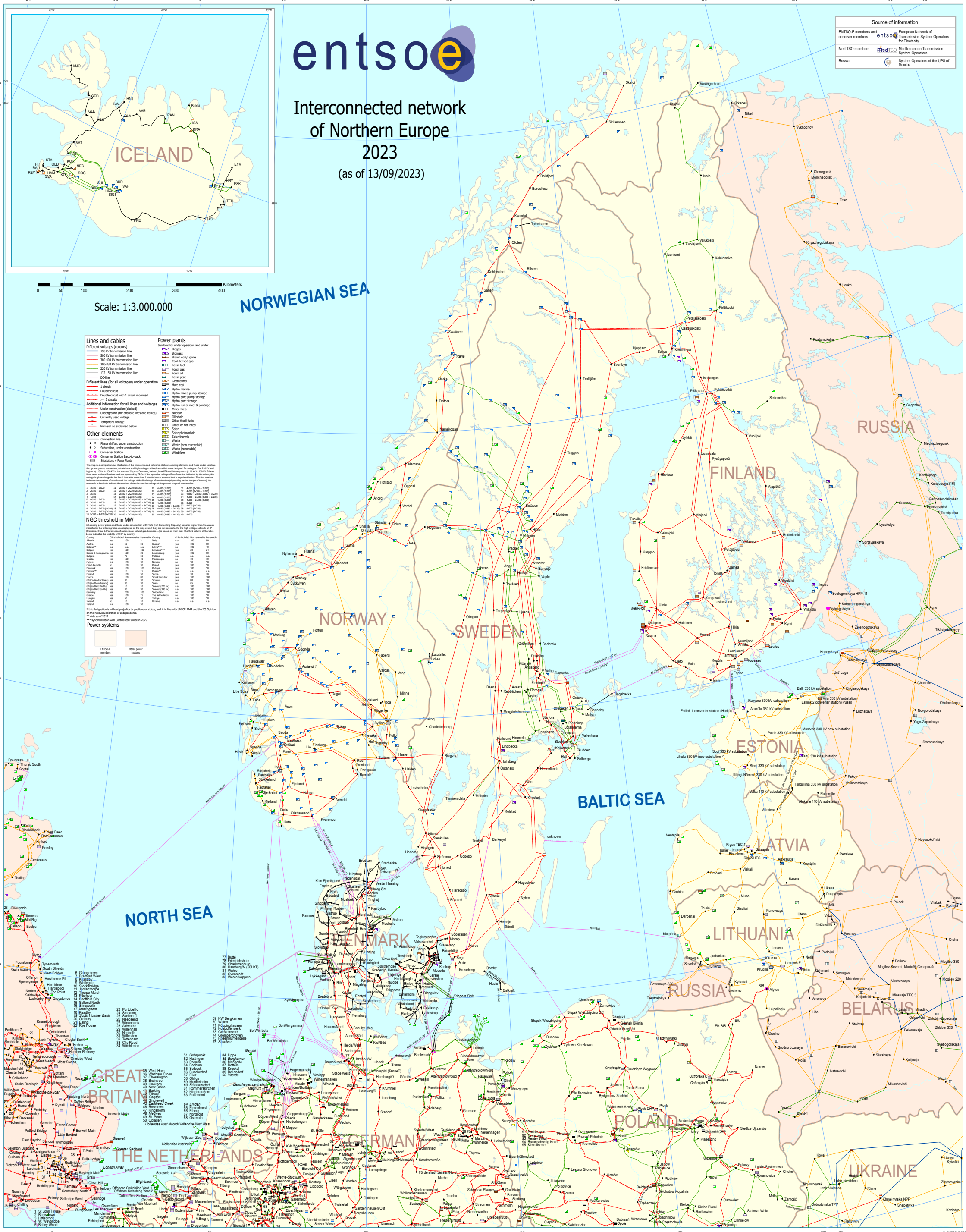

Figure A.1: Interconnected Network of Northern Europe[59]

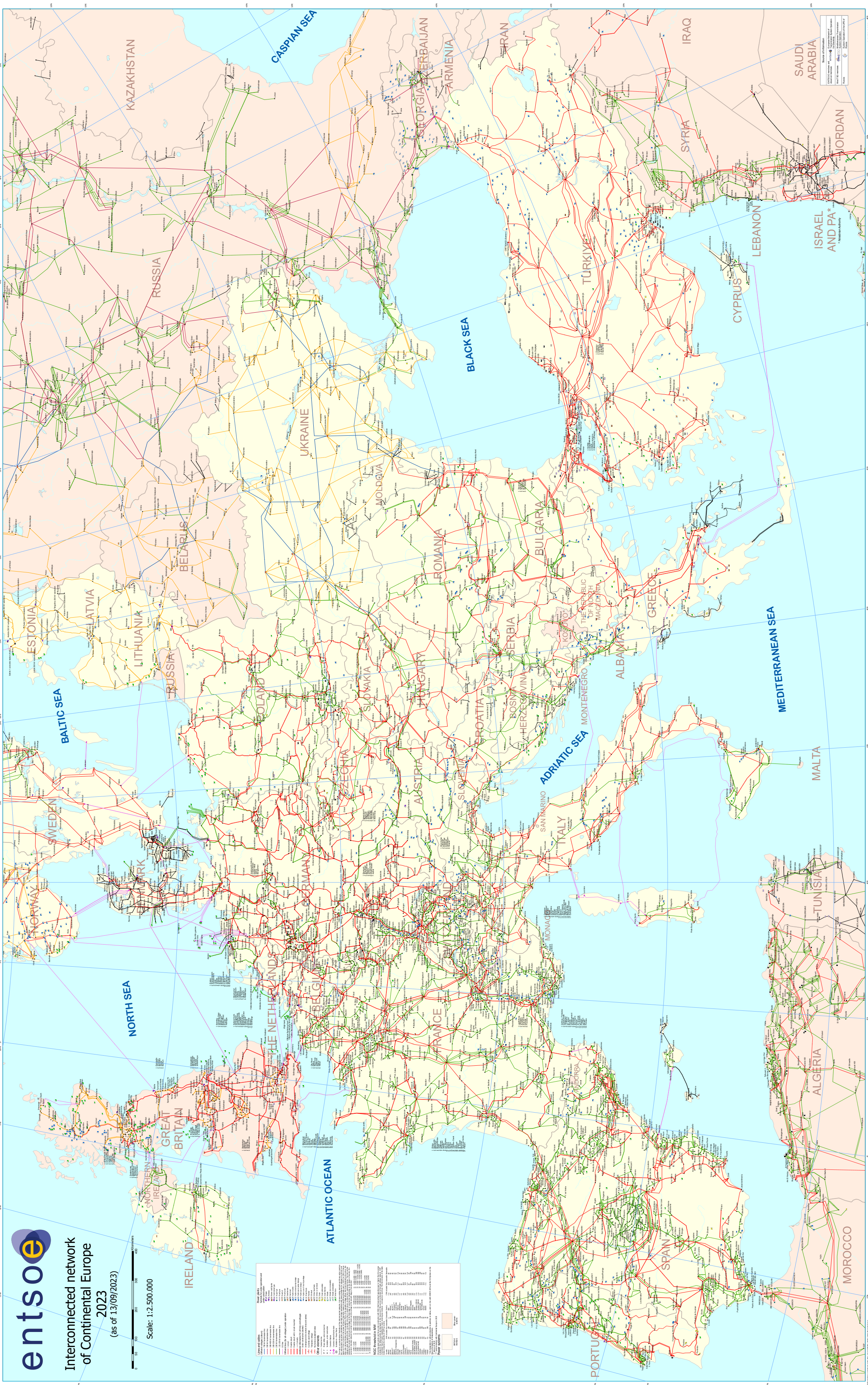

Figure A.2: Continental Europe Network[59]

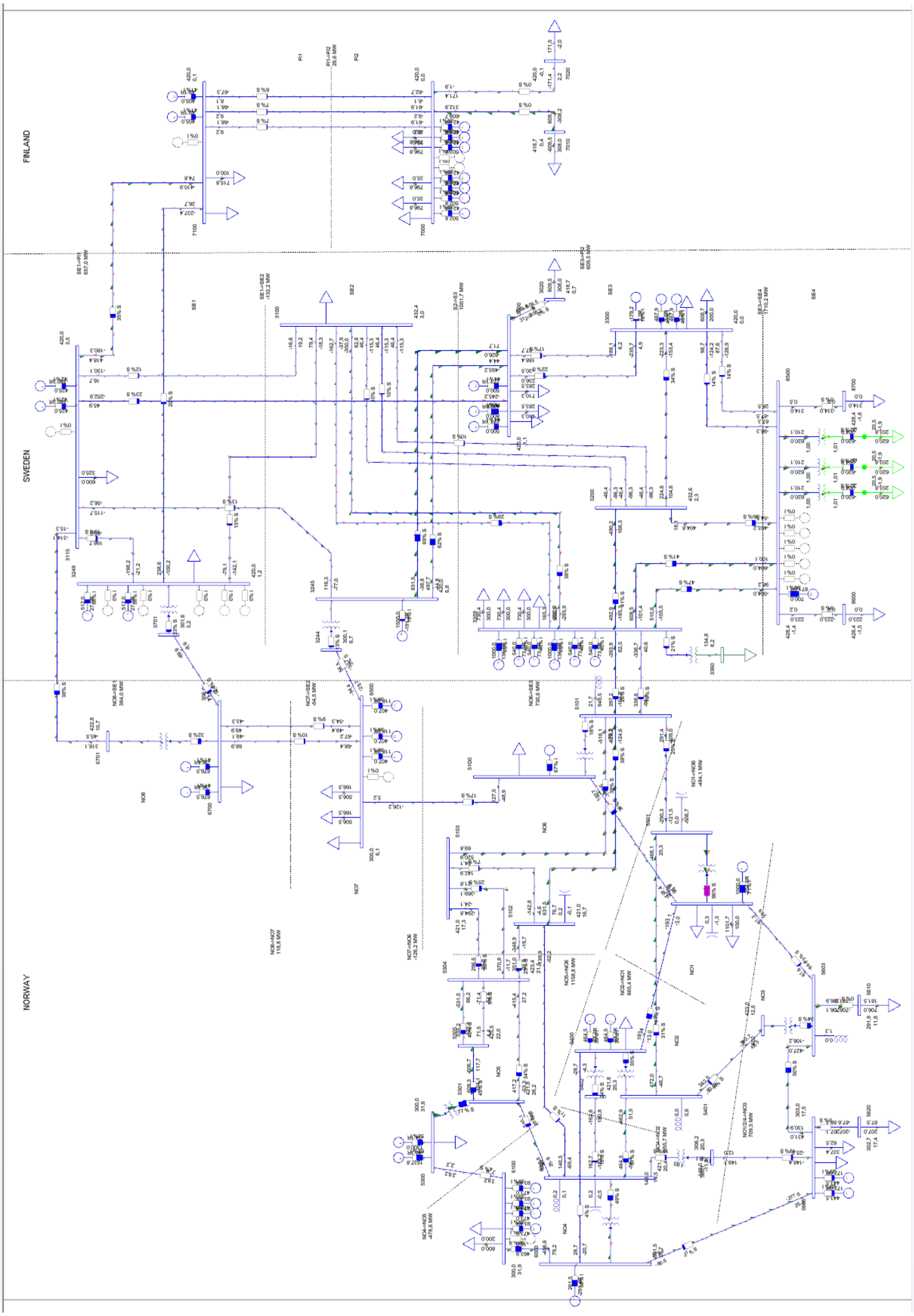

Figure A.3: Single line diagram of Nordic44 model in PSS/E

B

Appendix 2

B.1 Python PSS/E Framework

The code used for the simulations describing the sequential reconnection of the lines tripped is shown below. It describes the steps that were made from changing the parameters of the Nordic44 model during static and dynamic load flow simulation for the purpose of resynchronization of the two subsystems resulted from a disturbance that was created by line trips in the model.

```
###------ Import libraries ------###
import os
import sys
import math
import pandas as pd
import matplotlib.pyplot as plt

PSSE_LOCATION1: str = r"C:\Program Files\PTI\PSSE36\36.0\PSSBIN"
sys.path.append(PSSE_LOCATION1)
os.environ['PATH'] = os.environ['PATH'] + ';' +  PSSE_LOCATION1

PSSE_LOCATION: str = r"C:\Program Files\PTI\PSSE36\36.0\PSSPY311"
sys.path.append(PSSE_LOCATION)
os.environ['PATH'] = os.environ['PATH'] + ';' +  PSSE_LOCATION
import psse36
import psspy
import redirect
import time
import pssplot
import dyntools
from psspy import _i, _f, _s, _o

###------ Initialize PSSE ------###
redirect.psse2py()      #Redirect output from PSSE to Python
psspy.psseinit(0)       # Opens PSSE

ierr = psspy.report_output(islct=2, filarg= "output.txt") # Specify report output
    device. 6= no output. 1= PSSE GUI. 2= to a file
ierr = psspy.progress_output(islct=1)
ierr = psspy.alert_output(islct=2, filarg= "output.txt")
ierr = psspy.prompt_output(islct=2, filarg= "output.txt")

# LOAD SAVED CASE
psspy.case(r"""Z:\Master Thesis\NORDIC_44_Model\CASE14_single_line_resynchro\
    N44_T6_OLTC.sav""")
psspy.opendiagfile(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\N44_T6_OLTC.sld""")

# LOAD FLOW CALCULATION: FIXED DECOUPLED NEWTON-RAPHSON METHOD
psspy.fdns([0,0,0,1,1,0,99,0])

#------CHANGE VOLTAGE SET POINTS OF BUSES------#
```

```
psspy.bus_chng_4(3100,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3115,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3244,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3245,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3249,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3701,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(6500,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(6700,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(6701,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(7000,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(7010,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(7020,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(7100,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(1,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(2,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3000,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3020,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3200,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3300,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3359,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(3360,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5100,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5101,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5102,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5103,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5300,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5301,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5304,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5305,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5400,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5401,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5402,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5500,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5501,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5600,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5601,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5602,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5603,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5610,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(5620,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(6000,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(6001,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(6100,0,[_i,_i,_i,_i],[_f,0.9,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(8500,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(8600,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)
psspy.bus_chng_4(8700,0,[_i,_i,_i,_i],[_f,1.0,_f,_f,_f,_f,_f],_s)

# GENERATION INCREASE
psspy.machine_chng_5(3245,r"""1""",[_i,_i,_i,_i,_i,_i,_i],[2200.0,_f,_f,_f,_f,_f,_f
    ,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f],["",""])

# LOAD FLOW CALCULATION
psspy.fdns([0,0,0,1,1,0,99,0])
# SAVE THE NEW NETWORK DATA AND SINGLE LINE DIAGRAM
psspy.save(r"""Z:\Master Thesis\NORDIC_44_Model\CASE14_single_line_resynchro\
    N44_T6_OLTC_NEW.sav""")
psspy.savediagfile(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\N44_T6_OLTC_NEW.sld""")

# CONVERT GENERATORS FOR DYNAMIC SIMULATION
psspy.cong(0)
# ALL LOAD CONVERTED: 100% MVA LOAD
psspy.conl(0,1,1,[0,0],[100.0,0.0,0.0,100.0])
psspy.conl(0,1,2,[0,0],[100.0,0.0,0.0,100.0])
psspy.conl(0,1,3,[0,0],[100.0,0.0,0.0,100.0])
# LOAD DYNAMIC DATA FILE
```

```
psspy.dyre_new_2([1,1,1,1],r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\nordic44_newpss.dyr""")
# CHANNEL SETUP AND INITIALIZING OUTPUT FILE
psspy.chsb(0,1,[-1,-1,-1,1,1,0])
psspy.chsb(0,1,[-1,-1,-1,1,2,0])
psspy.chsb(0,1,[-1,-1,-1,1,3,0])
psspy.chsb(0,1,[-1,-1,-1,1,4,0])
psspy.chsb(0,1,[-1,-1,-1,1,5,0])
psspy.chsb(0,1,[-1,-1,-1,1,6,0])
psspy.chsb(0,1,[-1,-1,-1,1,7,0])
psspy.chsb(0,1,[-1,-1,-1,1,12,0])
psspy.chsb(0,1,[-1,-1,-1,1,14,0])
psspy.chsb(0,1,[-1,-1,-1,1,16,0])
psspy.strt_2([0,0],r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,3.0,9999,1,0)    # RUN FOR 3 SECONDS TO OBSERVE INITIAL SYSTEM

# TRIP LINES AND CREATED SYSTEM SPLIT
psspy.dist_branch_trip(3000,3245,r"""1""")
psspy.dist_branch_trip(3000,3245,r"""2""")
psspy.dist_branch_trip(3100,3359,r"""2""")
psspy.dist_branch_trip(3100,3359,r"""1""")
psspy.dist_branch_trip(3000,3115,r"""1""")
psspy.dist_branch_trip(5100,6500,r"""1""")
psspy.dist_branch_trip(3100,3200,r"""1""")
psspy.dist_branch_trip(3100,3200,r"""2""")
psspy.dist_branch_trip(3100,3200,r"""3""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,30.0,9999,1,0)   # RUN FOR 27 SECONDS

#------GENERATORS PARAMETERS (DYR FILE)------#
# CHANGING THE TURBINE-GOVERNOR IEESGO GAIN (K1) FROM 0
psspy.change_plmod_con(3000,r"""1""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3000,r"""2""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3000,r"""3""",r"""IEESGO""",7,0.9)   #AREA 1
# CHANGING THE HYDRO-GOVERNOR HYGOV DAMPING FACTOR (Dturb)
psspy.change_plmod_con(3245,r"""1""",r"""HYGOV""",11,0.7)   #AREA 2
# CHANGING THE HYDRO-GOVERNOR GAIN (At)
psspy.change_plmod_con(3245,r"""1""",r"""HYGOV""",10,1.2)   #AREA 2

# FIRST RECONNECTION MADE
psspy.dist_branch_close(3000,3245,r"""1""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,40.0,9999,1,0)

# SECOND RECONNECTION MADE
psspy.dist_branch_close(3000,3245,r"""2""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,50.0,9999,1,0)

psspy.change_plmod_con(3359,r"""1""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3359,r"""2""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3359,r"""3""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3359,r"""4""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3359,r"""5""",r"""IEESGO""",7,0.9)   #AREA 1
psspy.change_plmod_con(3359,r"""6""",r"""IEESGO""",7,0.9)   #AREA 1
# THIRD RECONNECTION MADE
psspy.dist_branch_close(3100,3359,r"""2""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,60.0,9999,1,0)

# FOURTH RECONNECTION MADE
psspy.dist_branch_close(3100,3359,r"""1""")
```

```
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,70.0,9999,1,0)

psspy.change_plmod_con(3115,r"""1""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(3115,r"""2""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(3115,r"""3""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(3115,r"""1""",r"""HYGOV""",10,1.1)   #AREA 2
psspy.change_plmod_con(3115,r"""2""",r"""HYGOV""",10,1.1)   #AREA 2
psspy.change_plmod_con(3115,r"""3""",r"""HYGOV""",10,1.1)   #AREA 2

# FIFTH RECONNECTION MADE
psspy.dist_branch_close(3000,3115,r"""1""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,80.0,9999,1,0)

psspy.change_plmod_con(5100,r"""1""",r"""HYGOV""",10,1.2)   #AREA 1
psspy.change_plmod_con(5100,r"""1""",r"""HYGOV""",11,0.7)   #AREA 1
psspy.change_plmod_con(6500,r"""1""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""2""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""3""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""4""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""1""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""2""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""3""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""4""",r"""HYGOV""",10,1.2)   #AREA 2

# SIXTH RECONNECTION MADE
psspy.dist_branch_close(5100,6500,r"""1""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,90.0,9999,1,0)

# SEVENTH RECONNECTION MADE
psspy.dist_branch_close(3100,3200,r"""1""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,100.0,9999,1,0)

# EIGHTH RECONNECTION MADE
psspy.dist_branch_close(3100,3200,r"""2""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,110.0,9999,1,0)

# NINTH RECONNECTION MADE
psspy.dist_branch_close(3100,3200,r"""3""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
psspy.run(0,130.0,9999,1,0)     # RUN FOR ANOTHER 30 SECONDS UNTIL SYSTEM STABLIZES

# EXPORTING THE DATA TO EXCEL FILE
pssplot.channelfileexcelexport(r"""Z:\Master Thesis\NORDIC_44_Model\
    CASE14_single_line_resynchro\CASE14_single_line_resynchro.out""")
```

Listing B.1: Sequential Reconnection

The code used for the simultaneous reconnection is the same as for the sequential reconnection. The only difference is the reconnection of the tripped lines where in the code the lines were all connected at the same time. A part of the code during the time of simultaneous resynchronization of the lines is depicted below.

```
# TRIP LINES AND CREATED SYSTEM SPLIT
psspy.dist_branch_trip(3000,3115,r"""1""")
psspy.dist_branch_trip(3000,3245,r"""1""")
```

```
psspy.dist_branch_trip(3000,3245,r"""2""")
psspy.dist_branch_trip(3100,3200,r"""1""")
psspy.dist_branch_trip(3100,3200,r"""2""")
psspy.dist_branch_trip(3100,3200,r"""3""")
psspy.dist_branch_trip(3100,3359,r"""1""")
psspy.dist_branch_trip(3100,3359,r"""2""")
psspy.dist_branch_trip(5100,6500,r"""1""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\CASE13_volt-
    freq_setpoints\CASE13_volt-freq_setpoints.out""")
psspy.run(0,30.0,9999,1,0)   # RUN FOR 27 SECONDS

# CHANGING THE TURBINE-GOVERNOR IEESGO GAIN (K1) IN AREA 1
psspy.change_plmod_con(3000,r"""1""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3000,r"""2""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3000,r"""3""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3359,r"""1""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3359,r"""2""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3359,r"""3""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3359,r"""4""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3359,r"""5""",r"""IEESGO""",7,0.9)
psspy.change_plmod_con(3359,r"""6""",r"""IEESGO""",7,0.9)

# CHANGING THE HYDRO-GOVERNOR HYGOV DAMPING FACTOR (Dturb)
psspy.change_plmod_con(5100,r"""1""",r"""HYGOV""",11,0.7)   #AREA 1
psspy.change_plmod_con(3115,r"""1""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(3115,r"""2""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(3115,r"""3""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(3245,r"""1""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""1""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""2""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""3""",r"""HYGOV""",11,0.7)   #AREA 2
psspy.change_plmod_con(6500,r"""4""",r"""HYGOV""",11,0.7)   #AREA 2

# CHANGING THE HYDRO-GOVERNOR GAIN (At)
psspy.change_plmod_con(5100,r"""1""",r"""HYGOV""",10,1.2)   #AREA 1
psspy.change_plmod_con(3115,r"""1""",r"""HYGOV""",10,1.1)   #AREA 2
psspy.change_plmod_con(3115,r"""2""",r"""HYGOV""",10,1.1)   #AREA 2
psspy.change_plmod_con(3115,r"""3""",r"""HYGOV""",10,1.1)   #AREA 2
psspy.change_plmod_con(3245,r"""1""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""1""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""2""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""3""",r"""HYGOV""",10,1.2)   #AREA 2
psspy.change_plmod_con(6500,r"""4""",r"""HYGOV""",10,1.2)   #AREA 2

# LINES RECONNECTION
psspy.dist_branch_close(3000,3115,r"""1""")
psspy.dist_branch_close(3000,3245,r"""1""")
psspy.dist_branch_close(3000,3245,r"""2""")
psspy.dist_branch_close(3100,3200,r"""1""")
psspy.dist_branch_close(3100,3200,r"""2""")
psspy.dist_branch_close(3100,3200,r"""3""")
psspy.dist_branch_close(3100,3359,r"""1""")
psspy.dist_branch_close(3100,3359,r"""2""")
psspy.dist_branch_close(5100,6500,r"""1""")
psspy.change_channel_out_file(r"""Z:\Master Thesis\NORDIC_44_Model\CASE13_volt-
    freq_setpoints\CASE13_volt-freq_setpoints.out""")
psspy.run(0,130.0,9999,1,0)
```

Listing B.2: Simultaneous Reconnection

B.2 Angle reset using MATLAB

Below is a code generated for extracting the angle data needed from the excel file created, then resetting the angles of the buses within the limit required and calculating the angle difference between them.

```
% Specify the file name and sheet
filename = 'comparison.xlsx';
sheet = ['10sec_interv']; % Specify the sheet name
% Read the data from the Excel file
data = xlsread(filename, sheet);

% Extracting the data from the specified rows and columns

% Apply reset method at the point of reconnection
reconnection_index = find(x >= 0, 1); % Find index of reconnection point
angle1_reset = y5;
angle2_reset = y6;

% Apply reset method for angle 1
for i = reconnection_index:length(y5)
    if angle1_reset(i) < -180
        angle1_reset(i:end) = angle1_reset(i:end) + 360;
    elseif angle1_reset(i) > 180
        angle1_reset(i:end) = angle1_reset(i:end) - 360;
    end
end

% Apply reset method for angle 2
for i = reconnection_index:length(y6)
    if angle2_reset(i) < -180
        angle2_reset(i:end) = angle2_reset(i:end) + 360;
    elseif angle2_reset(i) > 180
        angle2_reset(i:end) = angle2_reset(i:end) - 360;
    end
end

% Calculate new angle difference
angle_difference_reset = angle1_reset - angle2_reset;
angle_diff = angle_difference_reset;

% Apply reset method for angle difference
for i = reconnection_index:length(angle_difference_reset)
    if angle_diff(i) < -180
        angle_diff(i:end) = angle_diff(i:end) + 360;
    elseif angle_diff(i) > 180
        angle_diff(i:end) = angle_diff(i:end) - 360;
    end
end

% Plot the results
```

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