TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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THE USE OF DYNAMIC EQUIVALENTS IN THE REPRESENTATION OF NORDIC32 AND SIIRTOVERKKOMALLI AIMED AT TRANSMISSION CAPABILITY ASSESSMENTS

Master of Science thesis

Examiner: Prof. Enrique Acha
Examiner and topic approved by the Faculty Council of the Faculty of Computing and Electrical Engineering on 8th June, 2016

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master's Degree Programme in Electrical Engineering
TAIMOOR KHAN MEHMAND: The use of dynamic equivalents in the representation of Nordic 32 and Siirtoverkkomalli aimed at transmission capability assessments.
Master of Science Thesis, 87 pages, 12 Appendix pages
June 2016
Major: Smart Grids
Examiner: Professor Enrique Acha

Keywords: N32, DE.

Electrical energy is a standout amongst the most widely recognized forms of energy nowadays. Correspondingly, electrical power system is an essential part of any society. Nevertheless, the acquaintance of power business sector (electricity market) to power system and an initiation of power generation by the renewable energy resources have made power system simulations complex and more testing than prior. Hence, new methods for improving these simulations are required. Thus for the planning and operation of electric power systems, power system simulation is a vital tool. In this regard and back-ground, accomplishment of significant simulation results in the simulation has gotten to be one of the critical research questions in electrical power engineering field. Therefore, the best possible way to find out the solution for such questions is to create exact and robust models for the power system. In any case, the multifaceted nature and assorted qualities of power system components make the exact modelling hard and burdensome and demanding while the simulation is tedious. To adapt to the issue, high level modelling language is required that has the feature to realize the exact model representation and at the same time increment the computational efficiency of model simulation.

In this thesis, power system modelling and simulation is achieved using MATLAB/Simulink environment. This thesis focuses on the two different networks i.e. Siirtoverkkomalli (reflection of Finnish transmission network) and Nordic32 (reflection of Swedish transmission network in early 1990s). In addition to this, this thesis emphasizes on large scale power system modelling as well as dynamic performance of different generic network equivalents and tries to pursue the following objectives:

- The thesis initially reviews the power system dynamic equivalent (DE) theory which can be utilized for simplifying power system studies and power system reduction. Consequently, a comparison among the techniques for development of dynamic equivalent models is given for the identification of coherent generators.

- Secondly, an equivalent transmission grid model of Fin Grid Oy named 'Siirtoverkkomalli' is modelled and analyzed keeping in view the modelling principles of power systems. Then the implementation approach is reviewed

and discussed followed by the power transfer capability analysis with few tests for several network disturbances (Loss of line, three-phase-to-ground fault).

- Finally, the benchmark model of Swedish transmission network in early 1990s, i.e. N32, is modelled. Later, reduction of the of the N32 model by using dynamic equivalents is achieved. Lastly the equivalent model is connected to Siirtoverkkomalli and stability of the overall system is assessed.

A general conclusion is that by applying and adopting the appropriate power system simplification and reduction techniques, one can get enormous advantages in analyzing contemplating interconnected large power networks. In the majority of applications, power system reduction not just exceptionally lessens the multifaceted nature and assorted qualities of power system but also yield minute errors.

ACKNOWLEDGEMENT

At this point I would like to express my sincere gratitude and thanks to all the people who had an important contribution not only in my studies but generally in my life during my stay in Finland.

First of all, I would like to thank Prof. Enrique Acha and Mr. Tuomas Rauhala not only for giving me the opportunity to work on this project but also because of their continuous support, encouragement and positive interaction. Special thanks to Prof. Enrique Acha for his all the precious suggestions and guidance in the academic studies.

The research work has been carried out in the project: Dynamic performance of different generic network equivalents funded by Fin Grid Oy. I would like to thank all the project partners for the financial support.

I would also like to appreciate the effort made by my friend and colleague Mr. Ujjwal Datta for his kind assistance during my thesis.

Of course, I must thank my special friends, Mr. Saifullah Khan Mohmand and Mr. Kashif Ihsan Khattak, for their support and friendship. Our endless conversations will remain unforgettable.

My parents, of course, deserve the biggest gratitude for their endless love and support throughout my whole life. I also want to thank my brothers and sisters for being there for me during my studies and for the love and support throughout my life.

Last, but not least, I would like to dedicate this thesis to my Mom and Dad. You bring the greatest happiness to my life.

Taimoor Khan Mehmand

Tampere, 20.06.2016

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LIST OF SYMBOLS AND ABBREVIATIONS

GW	Giga watt
LFIO	Low frequency inter-area oscillations
N32	Nordic 32
DE	Dynamic Equivalent
EPRI	Electric Power Research Institute
RMS	Root Mean Square
PMU	Phasor Measurement Unit
PSCAD	Power System Computer Aided Design
ANN	Artificial Neural Network
THD	Total Harmonic Distortion
FACTS	Flexible Alternating Current Transmission Systems
OEL	Over Excitation Limiter
AVR	Automatic Voltage Regulator
TG	Turbine Governor
SW	South West
CW	Center West
CN	Center North
CE	Center East
CS	Center South
SE	South East
NW	North West
NE	North East
NETOMAC	Network Torsion Machine Control
SIN	National Integrated System
PSAT	Power System Analysis Toolbox
CEPEL	Center for Electrical Energy
DYNRED	Dynamic Reduction
SME	Synchronic Modular Equivalencing

M_i	inertial constant
δ_i	rotor angle
P_{mi}	mechanical input power
P_{ei}	electrical output power
D_i'	damping constant
ω_i	speed
$\Delta\delta_i$	change in rotor angle
ΔP_{mi}	change in mechanical input power
$\Delta\omega_i$	change in speed
I_R	the injection current vector of the remaining node
I_A	the injection current vector of the eliminated node
V_R	the voltage vector of the remaining node
V_A	the voltage vector of the eliminated node
Y_{RR}	the self-admittance of the remaining system
Y_{AA}	the self-admittance of the eliminated system
V_A	the voltage vector of the eliminated node

Y_{RA}	the mutual-admittance of the remaining system
Y_{AR}	the mutual-admittance of the eliminated system
$Y_{\_R}$	reflects a reduced equivalent network
$Y_{\_Ra}$	distribution matrix
U_0	voltage magnitude of the node
P_0	load active power
Q_0	load reactive power
Z_{bus}	Bus impedance

1. INTRODUCTION

1.1 Overview

With the advancement of technology, the demand of electrical energy has increased and it has led to making the demand of electricity, the parameter of development of a nation. An electrical utility company has to use its existing transmission capacity to feed the ever increasing demand of electricity, due to this the transmission lines have to be operated near their thermal stability limits [1]. Energy demand has substantially increased in the latter half of the 19^{th} century as evident from the studies below (Figure 1.1). Consumption of electric power continues to increase unabated due to urbanization. In order to accomplish sufficient transmission capacity and system security in an as efficient and economically viable manner as possible, the adoption and development of new technologies is studied continuously. In this regard, need of the hour is to seek new ways for the power to be generated and transmitted efficiently [2].

In order to have a secure and reliable operation of power systems, we need to counter the major hurdles and concerns i.e. Power system oscillation damping that mars the overall network efficiency and adds to the losses. It is evident that an increase in the power demand affects power system in such a way that power systems are driven closer to their limits, most importantly those of transmission capacity. This can be seen as a response to substantial increase in demand. Therefore, this is the reason why all system operators stick to their main goal i.e. to enlarge the transfer capability, while increasing the overall network efficiency and maintaining the system stable [3].

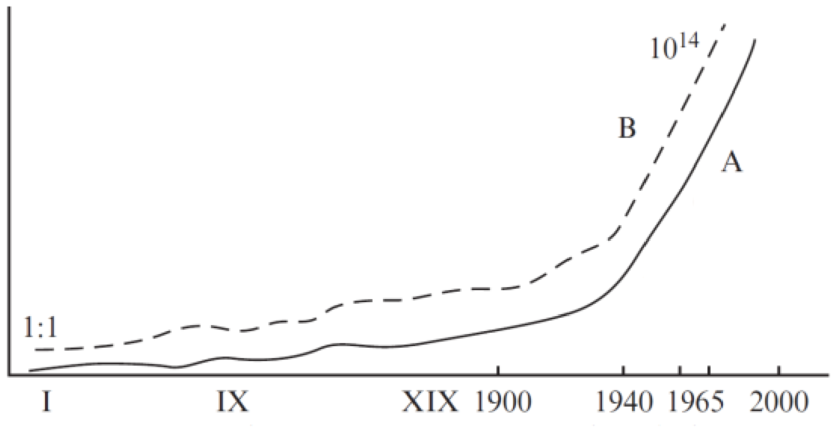

Figure 1. 1. (A): Total amount of energy consumption of humankind is 106 GW. (B): Total amount of stored information is 1014 bits. From prehistoric times to present days [1]

The smooth and steady operation of a power system is desirable to all system operators. Usually, power systems cannot operate in an unstable mode. In order for a system to be stable, a control system is designed considering various factors such as defining control parameters, control methods and objectives and classifying types and location of controllers. As a result, the purpose of damping oscillations is fulfilled. Hence, a control system is the usual remedy to counter an unstable system [4].

In the Nordic power system, there exists low-frequency inter-area oscillations (LFIOs) having inadequate damping which have a negative impact on stability constraints and thereby limit power transfer capacity. Damping enhancement to meet increasing demand is, therefore, indispensable in the Nordic grid [4] [5].

1.2 Motivation and objectives

The scope of the thesis is to construct, parameterize and test a generic transmission network model using MATLAB/Simulink including analysis of the impact of its different implementation approaches on dynamic network performance. In this Master's thesis project, the plan is to bring the Nordic32 as an extension of Siirtoverkkomalli in stages.

Need of the hour is to seek new ways for the power to be generated and transmitted efficiently because of the following barriers:-

- Increase in the power demand.
- Difficulty in energy source development.
- Power system oscillation damping.

This thesis aims at implementing and characterizing the dynamic response of the Nordic 32 system, using dynamic network equivalents. The model has been designed so that it will be capable to reflect various different aspects of technical performance of transmission network

- Transient stabilty.
- Frequency variations.

The MATLAB/Simulink environment will be used to conduct all aspects of modelling and simulation relating to this MSc project. The groups of coherent generators in Nordic 32 will be determined based on the generators' swing curves, corresponding to a wide range of network disturbances, such as changes in generation/load patterns, transmission line outages and short-circuit faults. Using network analysis techniques, the dynamic equivalents for the coherent generators are determined.

Following are the main objectives of this thesis:

1. To identify the coherent generator groups in Nordic 32.
2. Implementation of dynamic network equivalents.
3. Simulation studies in Siirtoverkkomalli with Nordic 32 dynamic equivalents.

1.3 Thesis outline

This thesis consists of six chapters. It begins with the introduction chapter which contains the objective of the thesis and the motivation behind the thesis. Chapter 2 discusses state of the art review discussing the power system dynamic equivalents while Chapter 3 explains the work done in implementing and developing the “Siirtoverkkomalli”. In other way around, it discusses the implementation and load flow calculation of “Siirtoverkkomalli”. Chapter 4 aims at implementing and characterizing the dynamic response of the Nordic 32 system, using dynamic network equivalents. Simulation Results of the thesis are presented in Chapter 3 and Chapter 4. Lastly, the thesis closes by summarizing the conclusions and suggesting the future possible areas of extending and continuing the work in Chapter 5.

2. Dynamic Network Equivalents

This chapter discusses State-of-the-art literature review of the Dynamic Network Equivalents. In the beginning of the chapter, a synoptic review of the previous work conducted on this topic is presented. Later on, a brief description on different techniques for development of dynamic equivalent models are highlighted. Lastly, the chapter is summarized.

2.1 State-of-the-art Review

The advent of new technology has brought a substantial increase in the electricity demand and its usage. The use of electricity has now become a factor of development of a nation. The production of electricity in conventional power system is carried out in large centralized power plants. The electricity produced is then transferred to the loads and customers using the transmission and distribution networks. The most complicated and enormous engineering system the world has ever witnessed is the electric power system, with the aim to generate, transmit and distribute electrical energy to areas widespread. In addition to this, the power system has to fulfill certain criterion or satisfy certain technical constraints [6]. These are:

- Generation and load must be in balance.
- Keeping the bus voltages in permissible range.
- Restraining the lines' overloading.

The sole purpose of electric power systems is to make sure that it has the ability to cover up wide geographical areas so that the inhabitants of urban and rural areas get equal shares of electrical energy. Due to the complexity in the nature of the power system, it is neither practical nor recommended to model and analyze the entire interconnected system for electromagnetic transient analysis analysis, on-line dynamic security assessment and off-line stability studies. Therefore, representing parts of the entire model by Dynamic Equivalents theory is a good practice while not disturbing the general dynamics and behavioural characteristics/features. However, modern computer programs for dynamic analysis are designed in such a way that they have the ability and capacity to handle and control hundreds to thousands of generators and buses. On the contrary, it is a hard task to analyze the system by solving the non-linear differential equations and concluding the results [7] [8]. So it becomes necessary to reduce the order of the system and to represent some parts of the system by dynamic equivalents. Dynamic equivalent studies can be taken up into two stages:-

- Identification of coherent groups of generators
- Representation of each coherent group by a dynamic equivalent machine

2.1.1 History of Power System Equivalents

Every power system in the world must be designed such that it can withstand the disturbances and must be ready to function properly in worst situation such as severe faults. Eventually the system collapses resulting in the disconnection of major portion of the system. While doing voltage studies and transient stability analysis, it is of prime interest to have a closer look at the dynamic behavior of the entire interconnected system. In this regard, for example one is frequently interested in testing and analyzing the specific part “A” of the system and on the other hand not really interested in remaining portion “B” of the system. Therefore, in order to reduce computational time and simulation time, the remaining part “B” can be represented by a certain set of simplified non-linear dynamic equation than that used for part “A”. The resulting set of simplified equations is the approximation and is also termed as the equivalent representation of “B” [9].

Dynamic equivalencing studies goes back to 1960’s [7] [8] .While analyzing a large system, the engineers are usually interested in the behavior of a certain part of the system. Such a part of the large system is called internal or study system and the rest of the system is referred to as external system. Static and dynamic reduction or equivalencing is the process of reducing the complexity of external system model while retaining its effect on the study system. The large electric power system models can be reduced significantly with this method while maintaining acceptable accuracy with respect to a specific phenomenon. The modal equivalents approach recognizes that some modes of oscillation will not be excited by disturbances in particular areas of the system and can therefore be eliminated. This method was never used extensively due to difficulty in determining the modes to be eliminated and due to the need to modify stability simulation programs to use a state matrix form of the equations of the equivalent [9] [10].

The aim of the dynamic equivalents is such that it must have the same characteristics or behavior as the original system. In order to have an exact equivalent model as the original system, different proposals on dynamic network equivalents need to be examined and studied. Usually, it is recognized that in the real system, each generator can have a different swing frequency when compared with all the other generators on the system. Therefore, the requirement for the equivalent in terms of performance as the real system, it is significant to simulate all the individual frequencies of the generators and also to provide as many generating units in the equivalent as there are in the real system. In that case, we have to compromise and sacrifice the simplicity of the system because it would not gain simplicity.

A perfect stability equivalent would perform exactly as the real system when viewed from any combination of retained buses. It is recognized that in the real system each generator can have a swing frequency that is different from all other generators on the system. Therefore, for the equivalent to perform like the real system it would be necessary to simulate all these individual frequencies. One way to accomplish this would be to provide as many generators in the equivalent as there are in the real system. But this would defeat the purpose of the equivalent since it would not gain simplicity. It appears that to gain simplicity by the use of a stability equivalent, it will be necessary to sacrifice accuracy. This raises the question of just how much inaccuracy can be tolerated.

The essence of equivalent is the reduction of large power systems into simple models having retained the performance of the real system. Usually, an equivalent is represented by only one machine to represent all those that were replaced on the real system. As a result of this approach, one attains simplicity and accuracy. On the other hand, the use of multiple machines raises questions whether how to utilize and treat the inertia of the eliminated machines so that we have an optimal performance of the overall system. Thus, the procedure is always open to question, and often a different stability equivalent was used to represent the same system on different occasions [11].

2.2 Dynamic Equivalent Models of Large Power Systems

It has been previously discussed and mentioned that the origin of dynamic equivalents and the research work related to it started in early 1960s. Further developments in this theory were put forward in 1970s and 1980s.

Modern day power system is becoming complex day by day due the extensive interconnection between the power systems. Due to this complexity, it is imperative to utilize the concept of dynamic equivalent networks so that a portion of the overall system is represented for the sake of simplicity. In this regard, the dynamic study analysis and simulation of large power systems is very time consuming and requires adequate computational effort. The gist of the dynamic equivalents is that the overall power system is classified into two areas, the study area and the external area. The study area needs to be well represented while the external area is replaced by dynamic equivalents. Implementation of a dynamic equivalent is carried out by the following steps [12]:

- Identification of coherent generators.
- Aggregation of generator terminal buses
- Elimination of load buses.
- Placing the coherent generators into groups, constructing the models and their control devices.

The dynamic simulation of large power systems is very time consuming and requires considerable computational effort. With the increasing size and complexity of modern interconnected power systems, it is imperative to use dynamic equivalents to represent some parts of these systems. Interconnected power systems are commonly partitioned into a study area that needs to be well represented and external areas that can be replaced by dynamic equivalents. The construction of a dynamic equivalent involves three steps. First, the identification of coherent generators, second, the aggregation of generator terminal buses and the elimination of load buses, and third, the aggregation of coherent generators models and their control devices.

The need for the dynamic equivalents came up because of the present day extensive interconnection within power systems which complicates the analytical procedure such as analysis of the steady state network performance for the purpose of system planning and operating problems. Due to the continual extension of the power systems nowadays, the analysis of the steady state network is getting more complicated. Equivalent circuits for the purpose of power flow studies must be developed so that the network analyzer studies are performed for the complete understanding and simplicity of the power system. This would eventually make life easy for power engineers. In this regard, we must seek new ways of preliminary simplification and reduction of the network. Early work on dynamic equivalents for large power systems was based on the ideas proposed by Ward [13]. These included empirical methods, such as replacement of all the generators within the external subsystem by one equivalent generator [14], or determination of equivalent generators, one for each boundary bus, from an empirical distribution of active powers and inertias of the external subsystem generators [15].

With the passage of time an alternative method was developed in 1970s that was based on the coherency identification concept. Coherency means that upon a remote disturbance some groups of generators swing together and can therefore be represented by a single equivalent machine. This coherency based concept was initially proposed by Albert Chang and Mahmood M. Adibi [16]. This method was further developed and incorporated in the Dynamic Equivalencing software package, DYNEQ, developed under the American Electric Power Research Institute (EPRI) [17] by Podmore [7].

Another coherency-based approach was developed and was known as “Slow coherency method”. In this method coherent machines are identified and placed in groups. Similar machines are placed in same group and then the dynamic equivalents are constructed as per the coherent groups. Later on it was developed and improved further for the coherency-based identification purposes. The idea behind the slow coherency technique is that whenever a large power system is facing any network disturbance of any kind, it is observed that weak oscillations start appearing due to formation of two groups of strongly coherent generators. In addition to this, the impedance of the overall network is modified such that it represents the coherent generators to analyze electric networks for different purposes [18]. Such as:

1. For power flow studies.
2. For network reconfiguration for loss reduction in distribution systems.

3. For frequency correction in power systems.

A unique class of coherency strategies is consolidated with structure protecting methods. The strategy begins with the identification of a coherent group utilizing the moderate coherency approach, trailed by the aggregation of generator terminal buses and elimination of load buses. The structure safeguarding method is connected on the coefficient lattices of the generators and related controls in the time space. Lastly, a technique known as structure preservation technique is applied [19, 20].

Different coherency measures to distinguish coherent generators groups have been proposed in view of linearized models. They incorporate swing curve of linearized frame-work [7], design acknowledgment [21], Root Mean Square (RMS) [22,23], coherency measures and coherency measure in view of the electromechanical distance measure [24,25] . A few different strategies are additionally reported in the writing which depend on the rate of change of kinetic energy of the faulted system [26] and utilizing the Lyapunov capacity [27] . The Lyapunov capacity strategy was enhanced in [28], where coherency of generators is resolved through some proposed coherency recognizable proof criteria in light of critical energy function during the post fault period. Different works proposed the calculation of the solitary point and admittance distance to recognize coherent generators [29]. This strategy was altogether enhanced in through a combination of faulted system dynamics, unstable equilibrium points and electrical coupling measure between generators. The faulted generator points are assessed through a Taylor series [31]. As of late, a few works proposed other coherency measures in view of manufactured neural systems, fuzzy methodology, spectrum analysis taking into account Taylor series extension and epsilon decay [35,36,37]. Synchronic modular equivalencing (SME) strategy has been proposed in light of the particular modular investigation and synchrony idea keeping in mind the end goal to distinguish the coherent groups of generators [40].

Several works implemented the clustering algorithm into the coherency identification procedure. In [41], the fuzzy C-Means clustering algorithm is used to identify the coherent groups for Taiwan power systems. The rotor angle of generator was applied as the coherency measures. Taking into benefits of Phasor Measurement Unit (PMU) measurements, the hierarchical clustering algorithm technique has been used in [42] to classify the generators into coherent groups. The generator's rotor measurements from PMU was utilized as the coherency measures. The proposed clustering method could be integrated into wide-area measurement system for fast identification of coherent generators. An application of coherency-based dynamic reduction for a large power system using the DYNRED program was developed by EPRI in 1993 [8, 17, 43]. The program included the techniques from the DYNEQ program and the slow coherency method [18]. DYNRED has had many successful applications in large power system studies. The program has been applied to perform dynamic reduction on three large North American power networks, to compare the stability performances of the reduced order models to those of the base model, by considering different operating conditions, power flow limits on critical interfaces, and sensitivity to fault location [17]. The DYNRED program was used in [43] to perform the aggregation of an excitation system using a trajectory sensitivity method to tune the equivalent parameters. However, the algorithm for parameter aggregation purposes has not been extensively tested [19, 44]

Recently, a software tool integrated with the Research Center for Electric Energy's (CEPEL) software package for determination of dynamic equivalents has been proposed in [45]. This software tool was developed to automate three steps of the dynamic equivalents process: identification of power plants that present coherence; static reduction of the network; and dynamic aggregation of the coherent generating unit models. The tools were applied to partially obtain a dynamic equivalent to the Brazilian National Interconnected System (SIN), and successfully reduced the size and complexity of the system with less time and computational effort. A simulation program Network Torsion Machine Control (NETOMAC) [46] offers a wide range of applications for power systems studies. The program incorporates an optimization/identification tool [47] for solving several optimization tasks and parameter identification problems. Three optimization algorithms, Quasi-Newton, Modified Powell and Least Square, are available in the program, offering robust identification and optimization of any linear and nonlinear problem in either the time or frequency domain [46].

Modular strategies have likewise been utilized to supplement the coherency techniques where coherent generators are distinguished utilizing modular techniques. The modular coherency system utilized the thorough numerical basis of the modular strategy to conquer the disservices of the coherency technique. Rather than the coherency equivalent, the modal equivalent does not rely upon the perturbation chosen to determine the equivalent. In the modular coherency strategy utilizing frequency response is applied to recognize coherent generators [23,48].

More recently, ANN-based models were proposed [49,50] to directly derive dynamic equivalents from measurements at points connecting both the study system and external subsystems. In these works, a neural network is used to extract states of the reduced order equivalent and another neural network is used to predict the new state values of the external system. Similar techniques successfully applied to derive dynamic equivalents for large systems are also presented in [51]. In these studies, the external system is represented through an input-output formulation and only one neural network is used to predict its dynamic behavior. Another approach in determining the dynamic equivalent is the identification approach using measurement and simulation-based techniques. The Maximum Likelihood technique is applied for online measurements in [52, 53] to identify parameter values for a specified equivalent structure, which is suitable for use in standard transient stability programs. In [54], parameter identification is carried out using a least-square algorithm with an adaptive step-size scheme. Firstly, a comparable model is assessed and re-assessed against the first framework until the cost capacity has achieved the base and every identical parameter have been recognized. The Broadened Two

Molecule Swarm streamlining calculation is applied in identification of the equivalent parameters for large power systems [55]. This technique connected the estimations got from Phasor Estimation Units (PMU).

More recently, the identification-based equivalent from online measurements, using the interpretation of coherency from the graph model of a power system, has been proposed in [56]. The information of coherent generators from a diagram model gives the quantity of identical generators and joining areas. At in the first place, the diagram model of the power framework is set up. Later, the coherent groups of generators are recognized from the frail connection of the chart model. At that point, the conglomeration of coherent generator buses is performed. At long last, the parameters of equivalent generators are recognized utilizing the identification method incorporated with the Power System Analysis Toolbox (PSAT) and MATLAB programming.

2.3 Techniques for Development of Dynamic Equivalent Models

2.3.1 Introduction

Over late decades, cutting edge power system networks have enormously expanded in size and unpredictability because of the developing interest for power. Thus, much exertion has been put into the advancement of proficient computational strategies for system stability and soundness investigations of complex power systems. The most well-known technique is to diminish the many-sided quality of the substantial system to the computationally achievable size of an equal framework, which holds the dynamic characteristics of the power system with sensible precision. The procedure of diminishing an extensive force framework system into an equivalent model for dynamic system analysis is called Dynamic Equivalencing.

For the most part, when creating a dynamic equivalent, the overall system can be classified into an internal framework and an external framework. The internal system is the comprehensive and nitty gritty representation of the study system that is to be held. Whatever is left of the power system network, the external system, as appeared in Figure 2.1 [57], must be decreased by the process of dynamic equivalencing prepare and is for the most part characterized by an arrangement of nodes/buses which are persistently interconnected and connected to the interior framework by means of boundary nodes/buses [57]. Dynamic equivalencing is the procedure of decreasing the order of the external system, and the subsequent dynamic identical model speaks to the external system amid investigations of the internal system. The most vital element of an dynamic equivalent model is the capacity to exhibit the dynamic conduct of the original external system.

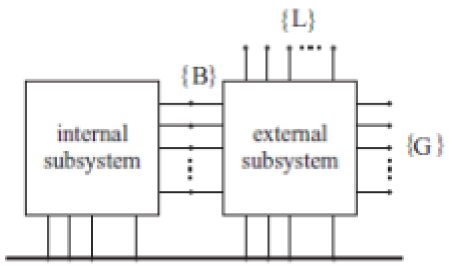

Figure 2.1: Internal and external subsystem: {B}, boundary nodes, {L}, load nodes, {G}, [57]

Shortly, the two main techniques for developing the dynamic equivalent model will be discussed. Two fundamental ways for the development and improvement of dynamic equivalents are: conventional methods and measurement and simulation based methods. Detailed descriptions of the two approaches to dynamic equivalencing are presented in Sections 3.2 and 3.3

2.3.2 Conventional Techniques

The two methods that lies under the conventional techniques are essentially the coherency methods and the modal analysis method. It has been observed that both methods have a common approach for dynamic equivalencing i.e. model reduction approach which includes diminishing or aggregation of some components of the existing model.

2.3.2.1 Modal Analysis Method

Modal methods [58] are based on the linearized state space model of the external system. The equation for the state space model of the external system is given as under:

$$G:\begin{cases}\dot{x} = Ax + Bu, & x(0) = x_0 \\ y = Cx + Du\end{cases} \tag{2.1}$$

where G is a state space system, A, B, C and D are the system matrices, u and y represent the vectors of the input and output variables and x is the state of the model. Using the modal method, the reduced order system of G represents by Gr, is defined as:

$$G_r:\begin{cases}\dot{z} = A_r x + B_r u, & z(0) = z_0 \\ y_r = C_r x + D_r u\end{cases} \tag{2.2}$$

where G_r should be of lower order than G. A_r, B_r, C_r and D_r represent the reduced system matrices, y_r is the output variable for reduced system and z is the state of the reduced model.

Eigenvalues of the system matrix A give the modes of the dynamic system. The complex conjugate eigenvalues give oscillatory modes and the real eigenvalues give non-oscillatory modes. At the point when a system experiences a transient conduct because of an aggravation, the oscillatory modes with high damping decay quicker than the modes with lower damping. Modular strategies attempt to remove the moderately less damped modes (represented by eigenvalues of A which are nearer to the starting point) and evacuate the exceptionally damped modes (represented by eigenvalues of A which are farthest far from the starting point). The moderately less damped modes are available in the system time responses over a more drawn out period and subsequently exhibit and determine the general system response.

Various model reduction techniques can be applied in “modal analysis method”. These different techniques applied has to fulfill certain criterion i.e. depending upon the characteristics and structure of the external system that must be held or retained in the reduced order model. In this regard, there are few techniques under the heading of “modal analysis method” which will be discussed in the upcoming sections. Namely:

- Model Truncation
- Balanced Realization
- Optimal Hankel-norm
- Singular perturbation theory

2.3.2.1.1 Model Truncation

This type of model reduction technique utilizes the concept of directly identifying and retaining certain modes of interest and value. It was the pre-eminent model reduction technique applied to electric power systems. The method presented is capable of accurately representing, the dynamical effects of generator field and amortisseur windings, voltage regulators, and speed governors. This approach is based on the pole location of the linear system. Modal truncation actually ignores fast dynamic phenomena and it is reasonable for steady state application. Nonetheless, in transient behavior, fast dynamic elimination leads to inaccuracy in the model’s performance [59,60,61].

Good approximation of G_r can often be obtained by means of modal truncation. Firstly, change the coordinates of *x(t)*. That is, find a suitable invertible matrix T€ R^{nxn} and transform the state space model of (3-1) according to,

$$\bar{A} = T^{-1}AT = \begin{pmatrix} \bar{A}_{11} & \bar{A}_{12} \\ \bar{A}_{21} & \bar{A}_{22} \end{pmatrix}, \bar{A}_{11} \in \Re^{r \times r} \qquad \bar{B} = T^{-1}B = \begin{pmatrix} \bar{B}_1 \\ \bar{B}_2 \end{pmatrix}, \bar{B}_1 \in \Re^{r \times m},$$
$$\bar{C} = CT = \begin{pmatrix} \bar{C}_1 & \bar{C}_2 \end{pmatrix}, \bar{C}_1 \in \Re^{p \times r}, \qquad \bar{D} = D \tag{2.3}$$

Modal truncation is therefore define by G_r in (3.2) as,

$$\begin{aligned} A_r &= \bar{A}_{11}, \quad B_r = \bar{B}_1 \\ C_r &= \bar{C}_1, \quad D_r = \bar{D} \end{aligned} \tag{2.4}$$

2.3.2.1.2 Balanced Realization

Balanced realization is a type of model reduction technique in which the emphasis is mainly on the observability and controllability characteristics of the system under test. This strategy utilizes somewhat distinctive methodology, since it depends on the input and output conduct of the framework/system. For the most part, the state space system is changed into another representation, such that the property of every state space variable is both controllable and discernible. Keeping in mind the end goal to accomplish a reduce model, states that are emphatically impacted by the inputs and unequivocally associated with the outputs are retained, while states that are feebly controllable and detectable are truncated or evacuated [58].

The Controllability Gramian, P, is a measure of how much the input energy is coupled to the states. The Observability Gramian, Q, is a measure of how the states and the output are coupled to each other. For the given state-space model of G in (3.1), the Controllability and Observability Gramians, P and Q are defined as [58]:

$$P = \int_0^\infty e^{A\tau} B B^T e^{A^T \tau} d\tau \tag{2.5}$$

$$Q = \int_0^\infty e^{A^T \tau} C^T C e^{A\tau} d\tau \tag{2.6}$$

P and Q, respectively, can be obtained by solving the following Lyapunov equations [58]:

$$\begin{aligned} AP + PA^T + BB^T &= 0 \\ A^T Q + QA + C^T C &= 0 \end{aligned} \tag{2.7}$$

The Hankel singular values of G are denoted as:

$$\sigma_i\left(G(s)\right) = \sqrt{\lambda_i\left(PQ\right)}, \quad i = 1, 2, \ldots, n \tag{2.8}$$

where $\sigma_1 \geq \sigma_2 \geq ... \geq \sigma_n \geq 0$. Usually the σ_i are placed in a matrix as:

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_n \end{bmatrix} \tag{2.9}$$

The balanced realization is achieved when P and Q become equal to each other and to the Σ matrix as shown in (3.10).

$$\bar{P} = \bar{Q} = \Sigma \tag{2.10}$$

Then the balanced system of G is partitioned as:

$$A = \begin{bmatrix} \tilde{A}_{11} & \tilde{A}_{12} \\ \tilde{A}_{21} & \tilde{A}_{22} \end{bmatrix}, B = \begin{bmatrix} \tilde{B}_1 \\ \tilde{B}_2 \end{bmatrix}, C = \begin{bmatrix} \tilde{C}_1 & \tilde{C}_2 \end{bmatrix}, D = \tilde{D} \text{ and } \Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix} \tag{2.11}$$

where $\Sigma_1 = \text{diag}(\sigma_1, \sigma_2, ..., \sigma_k)$ and $\Sigma_2 = \text{diag}(\sigma_{k+1}, \sigma_{k+2}, ..., \sigma_n)$

The reduced model of Gr is defined as:

$$\begin{aligned} A_r &= \tilde{A}_{11}, \quad B_r = \tilde{B}_1 \\ C_r &= \tilde{C}_1, \quad D_r = \tilde{D} \end{aligned} \tag{2.12}$$

2.3.2.1.3 Optimal Hankel-norm

Hankel-standard estimation [62-63] is a model decrement method that tries to accomplish a trade-off between a little most pessimistic scenario error and a small energy error. If the transfer function of the system described by (3.1) is denoted by H(s), the reduced order method based on the Hankel norm attempts to find a transfer function of k-th order truncated system, $H_k(s)$, which minimizes the error of the approximation as,

$$\left\| H(s) - H_k(s) \right\|_{\infty} = \sigma_{k+1} \tag{2.13}$$

In view of (2.13), the largest error between the exchange capacity of the real and reduced system for all frequencies will be not exactly or equivalent to k+1 of Hankel particular value.

2.3.2.1.4 Singular Perturbation Theory

Singular perturbation theory is the most prominent and popular method, lying between the already specified techniques and utilizing the distinctive time scale of the power systems. In the singular perturbation hypothesis strategy, the external system is isolated into quick and moderate progression frameworks or fast and slow dynamics systems. The fast dynamic system can be disregarded and its impact will be reintroduced as a limit layer amendment acquired utilizing a different time scale. Accordingly, the strategy is by all accounts a more proper diminishment procedure than those portrayed already. The upsides of this method are that it holds the physical significance of variables and can anticipate both relentless state/steady state and transient conduct of the system in light of the fact that the impacts of fast dynamics are reintroduced in the reduced model [60, 61].

The state space model of G_r in (3.2) using singular perturbation method is defined as,

$$\begin{aligned} A_r &= \bar{A}_{11} - \bar{A}_{12}\bar{A}_{22}^{-1}\bar{A}_{21}, \quad B_r = \bar{B}_1 - \bar{A}_{12}\bar{A}_{22}^{-1}\bar{B}_2 \\ C_r &= \bar{C}_1 - \bar{C}_2\bar{A}_{22}^{-1}\bar{A}_{21}, \quad D_r = \bar{D} - \bar{C}_2\bar{A}_{22}^{-1}\bar{B}_2 \end{aligned} \tag{2.14}$$

following from (3.3).

2.3.2.2 Coherency-based Methods

Coherency means that upon a remote disturbance some groups of generators swing together and can therefore be represented by a single equivalent machine. Coherency-based methods are widely used dynamic equivalencing method in which the coherent generators in the external area are accumulated and supplanted by comparable models. Crucks of the matter is that the generators’ response is closely observed and analyzed during post fault condition or post fault transient disturbance. In addition to this, it is also observed that only those generators nearer to the fault carry on as individual units while the groups of generators further from the fault location have a tendency to sway together. In other words, the angular difference of generators in each group remains constant within a certain tolerance. The need for the coherency-based methods was necessary to have simplified representations, or equivalents to represent those parts of the system which has an impact on the overall system performance but whose internal performance is not under examination. The coherent grouping of generators is done by analyzing the behavioral response of the power system after a large disturbance causes a change in the system conditions [7,64]. To summarize the dynamic equivalencing by coherency-based methods, the following steps are involved:

1. Identifying coherent generator groups.
2. Dynamic accumulation of generating unit models.
3. Network Reduction.

2.3.2.2.1 Identifying Coherent generator groups

With a specific end goal to determine the coherency, a swing equation is utilized to evaluate rotor speed. The generator swing condition [65] is given by:

$$\frac{d}{dt}\delta_i = \omega_i \tag{2.15}$$

$$M_i \frac{d^2}{dt^2}\delta_i = P_{mi} - P_{ei} - D_i'\omega_i \tag{2.16}$$

Where M_i : inertial constant

δ_i : rotor angle

P_{mi} : mechanical input power

P_{ei} : electrical output power

D_i' : damping constant

ω_i : speed

Therefore after linearization, the following linearized system model is obtained:

$$M_i \frac{d^2}{dt^2}\Delta\delta_i = \Delta P_{mi} - \Delta P_{ei} - D_i'\Delta\omega_i \tag{2.17}$$

Where $\Delta\delta_i$:change in rotor angle

ΔP_{mi} : change in mechanical input power

$\Delta\omega_i$: change in speed

For a given disturbance, coherent generators are determined if every generator within the group have the same angular speed and a constant complex ratio of the terminal bus voltage [66]. The following measure is proposed for identification of coherent groups [57], in which two terminal generator buses i and j are defined to be coherent if

$$\frac{\underline{V}_i(t)}{\underline{V}_j(t)} = \frac{V_i(t)}{V_j(t)} e^{j[\delta_i(t)-\delta_j(t)]} = \frac{V_i(t)}{V_j(t)} e^{j[\hat{\delta}_i-\hat{\delta}_j]} = \underline{\vartheta}_i \tag{2.18}$$

If the voltage magnitude can be assumed to be constant, the coherency condition (3-18) simplifies to $\delta_i(t) - \delta_j(t) = \delta^{\wedge}_{ij}$ where $\delta^{\wedge}_{ij} = \delta_i - \delta_j$ are the initial values.

2.3.2.2.2 Dynamic accumulation of generating unit models

In this section the basic idea is to consolidate the models for each coherent group of production unit into one or a few identical models. This is also known as dynamic aggregation step and the coherency of the generator internal buses is also assumed in this step. The procedure for the generator aggregation is illustrated in Figure 2.2. Initially the network model contains numerous generator and load nodes i.e. $\{G\}=\{G_1\}+\{G_2\}+ \ldots +\{G_g\}$. These generator nodes are then distinguished into groups a coherent generator nodes as $\{G_1\},\{G_2\}, \ldots ,\{G_g\}$. Finally each of the groups is replaced by identical generating unit.

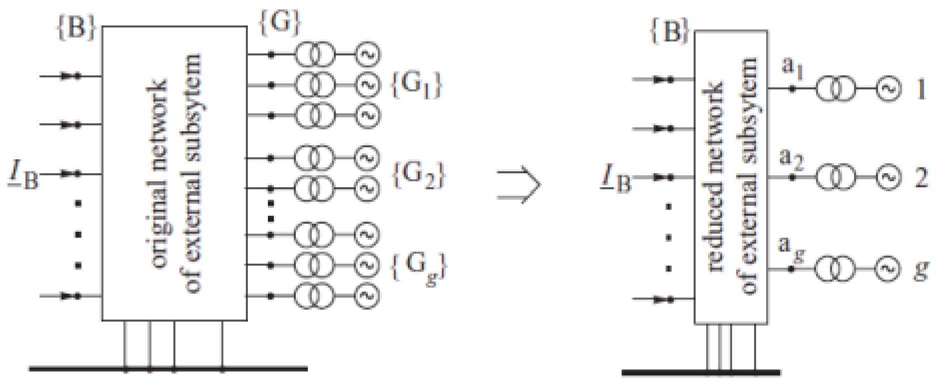

Figure 2.2: Generator aggregation [57]

By and large, the generator aggregation can be classified into two categories, the classical aggregation and detailed aggregation. In classical aggregation, the coherent groups are represented by an equivalent classic generator model. The equivalent generator model incorporates the sum of the inertia and proportionate transient reactance. On the contrary, the detailed aggregation includes the descriptive generator model adding excitation system, governor circuits and power system stabilizers [43,44].

2.3.2.2.3 Reducing the network

The last step in the dynamic equivalencing utilizing the coherency-based technique is network reduction. The prime objective in this part is to eliminate all the left over nodes and pie sections or transmission lines from the network [57]. The elimination of nodes is illustrated in Figure 2.3 as follows:

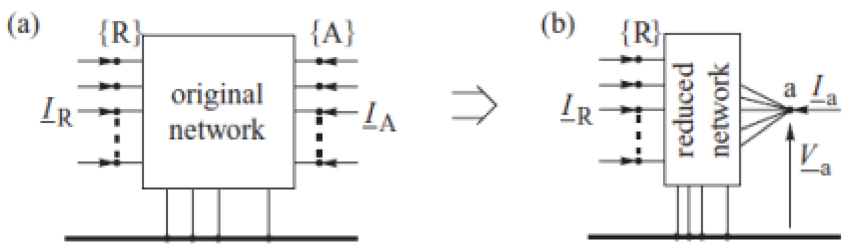

Figure 2.3: Elimination of nodes: (a) network before elimination; (b) network after elimination. {A}, set of eliminated nodes {R}, set of retained nodes. [57]

The network is described by the following nodal equation [57]:

$$\begin{bmatrix} \underline{I}_R \\ \underline{I}_A \end{bmatrix} = \begin{bmatrix} \underline{Y}_{RR} & \underline{Y}_{RA} \\ \underline{Y}_{AR} & \underline{Y}_{AA} \end{bmatrix} \begin{bmatrix} \underline{V}_R \\ \underline{V}_A \end{bmatrix} \tag{2.19}$$

where, I_R : the injection current vector of the remaining node

I_A : the injection current vector of the eliminated node

V_R : the voltage vector of the remaining node

V_A : the voltage vector of the eliminated node

Y_{RR} : the self-admittance of the remaining system

Y_{AA} : the self-admittance of the eliminated system

Y_{RA} : the mutual-admittance of the remaining system

Y_{AR} : the mutual-admittance of the eliminated system.

The eliminated voltages and currents can be swapped using simple matrix algebra to give

$$\begin{bmatrix} \underline{I}_R \\ \underline{I}_a \end{bmatrix} = \begin{bmatrix} \underline{Y}_{RR} & \underline{Y}_{Ra} \\ \underline{Y}_{aR} & \underline{Y}_{aa} \end{bmatrix} \begin{bmatrix} \underline{V}_R \\ \underline{V}_a \end{bmatrix} \tag{2.20}$$

Where

$$\underline{Y}_{RR}\underline{V}_R + \underline{Y}_{RA}\underline{V}_A = \underline{Y}_{RR}\underline{V}_R + \underline{Y}_{Ra}\underline{V}_a$$

The square matrix in equation (2.20) is the partial inversion of the admittance matrix. The nodal currents in the set {R} are,

$$\underline{I}_R = \underline{Y}_R\underline{V}_R + \Delta\underline{I}_R \tag{2.21}$$

The above equation (2.21) gives information about the currents and voltages of the left over nodes in the eliminated network.

$\Delta\underline{I}_R = \underline{Y}_{Ra}\underline{I}_E$ is the vector consisting of the equivalent currents replacing eliminated nodes

And $\underline{Y}_R$: reflects a reduced equivalent network

$\underline{Y}_{Ra}$: distribution matrix

2.3.3 Measurement and Simulation-based Techniques

Over the decades, various techniques have been proposed and implemented for developing the dynamic equivalent models each having its pros and cons. In this regard, measurement and simulation-based techniques utilize real time data or measurements of the power systems. These are classified into two types. These are:

1. Artificial Neural Network (ANN)-Based Method
2. System Identification Method

2.3.3.1 Artificial Neural Network(ANN)-based Method

This model contains a substantial number of parameters, which can be balanced by a reasonable preparing procedure to build up the element of a mind boggling framework. A neural system can be prepared to create the dynamics of a given framework. Knowing present and past input values and the past output values, the present value of the outputs is a nonlinear function of former signals. Further details of the method can be found in [67].

2.3.3.2 System Identification Method

The system identification strategy alludes to the determination of the key attributes of a dynamic framework by watching the reaction of system variables to irregular system inputs, either normal or deliberate. The goal is to appraise an arrangement of parameters having a place with a model that is accepted to depict a proportion of an aggregated framework, in light of input and output estimations and measurements. Along these lines, the technique does not require distinguishing proof of definite data about the subsystem. In this manner, the quintessence of system identification comprises of coordinating signs from a real system that is experiencing irregular perturbations with the same signals ascertained on a model of the system, and enhancing the model to decrease the difference. System identification method is illustrated in the Figure 2.4 and further details of the method can be found in [68].

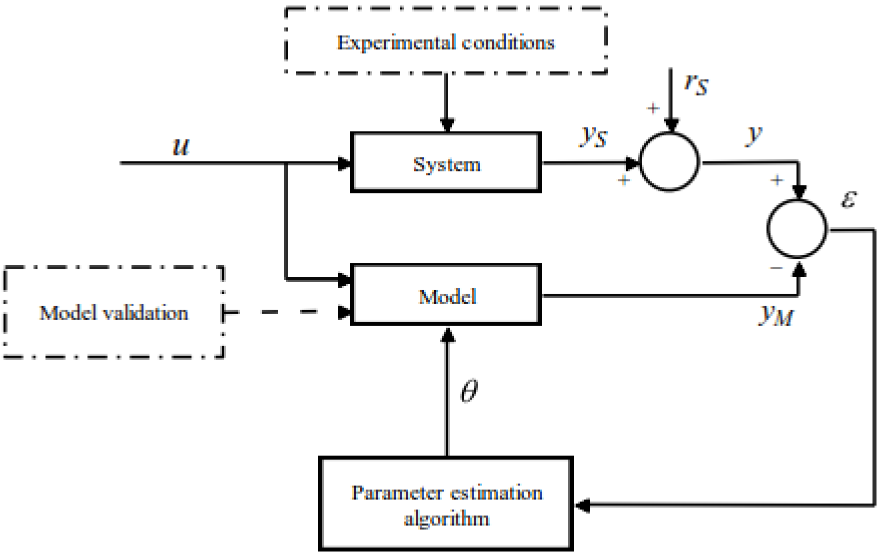

Figure 2.4: Principle of system identification procedure [68]

3. Fin Grid Siirtoverkkomalli

In this chapter, an equivalent transmission grid model of Fin Grid Oy named ‘’Siirtoverkkomalli’’ is studied, modelled and analyzed. Then the implementation approach is reviewed and discussed. Lastly different power transfer capability analysis has been done with few tests conducted for several circumstances.

3.1 System Overview and Characteristics

Siirtoverkkomalli" i.e. transmission network model is a generic network reflecting the structure of Finnish network. An equivalent transmission grid model of Fin Grid Oy named ‘’Siirtoverkkomalli’’ has been studied and analyzed. This network is more real network oriented rather a traditional equivalent network. The main focus was on different amount of power transfers capability analysis without compensation, network stability at fault conditions. The model has been implemented so far only using PSCAD and has been designed so that it will be capable to reflect various different aspects of technical performance of transmission network i.e. transient stability, frequency variations and phenomena in series compensated network. In addition to this, the structure of the network has been established but the dynamic performance is still under finalization. In this regard, efforts are need to be made for more extensive testing starting from basic load flow simulation. A general graphical outline of the network (Siirtoverkkomalli and Scandinavia) is illustrated in Figure 3.1.

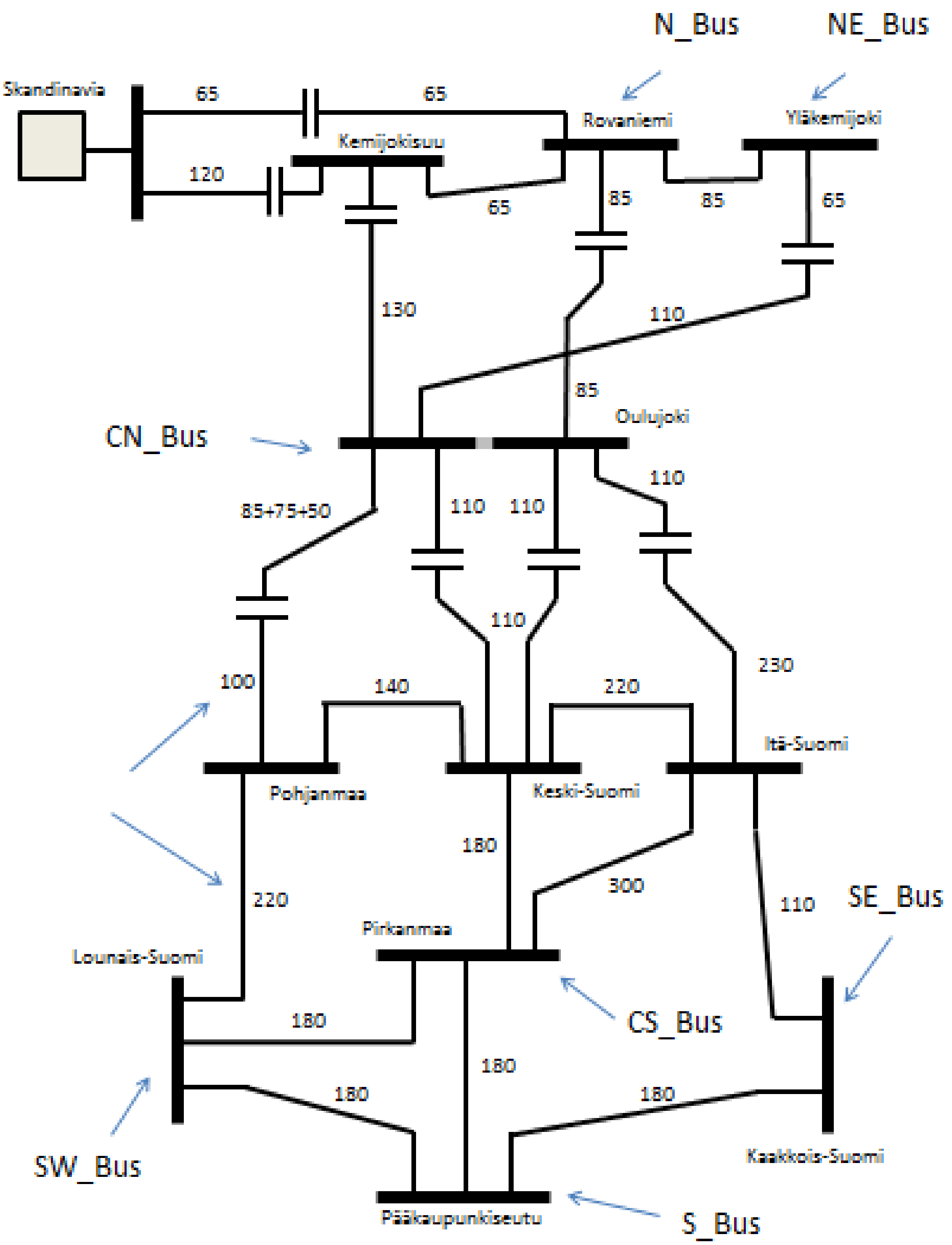

Figure 3.1: Outline of the Siirtoverkkomalli and N32 system

For the purpose of testing and analysis, it was decided to implement the same model using MATLAB /Simulink. With necessary component models and blocks available in SimscapePower Systems^{TM} (formerly SimPowerSystems^{TM}) , it is theoretically feasible to implement and simulate the network model utilizing MATLAB/Simulink environment. Simscape Power Systems^{TM} provides component libraries and analysis tools for modeling and simulating electrical power systems. It includes models of electrical power components, including three-phase machines, electric drives, and components for applications such as flexible AC transmission systems (FACTS) and renewable energy systems. Harmonic analysis, calculation of total harmonic distortion (THD), load flow, and other key electrical power system analyses are automated, helping you investigate the performance of your design [69]. The one-line diagram of the equivalent model of Siirtoverkkomalli and Nordic 32 is shown in Figure 3.2 below.

The system consists of four different geographical areas with different production and consumption characteristics.

- 'North' with low levels of Hydro generation and high level of consumption.
- 'Central' with Steam generation and high level of consumption.
- 'South' with high levels of Nuclear generation and moderate Steam generation with high load
- 'Nordic' with high levels of Hydro and Steam generation.

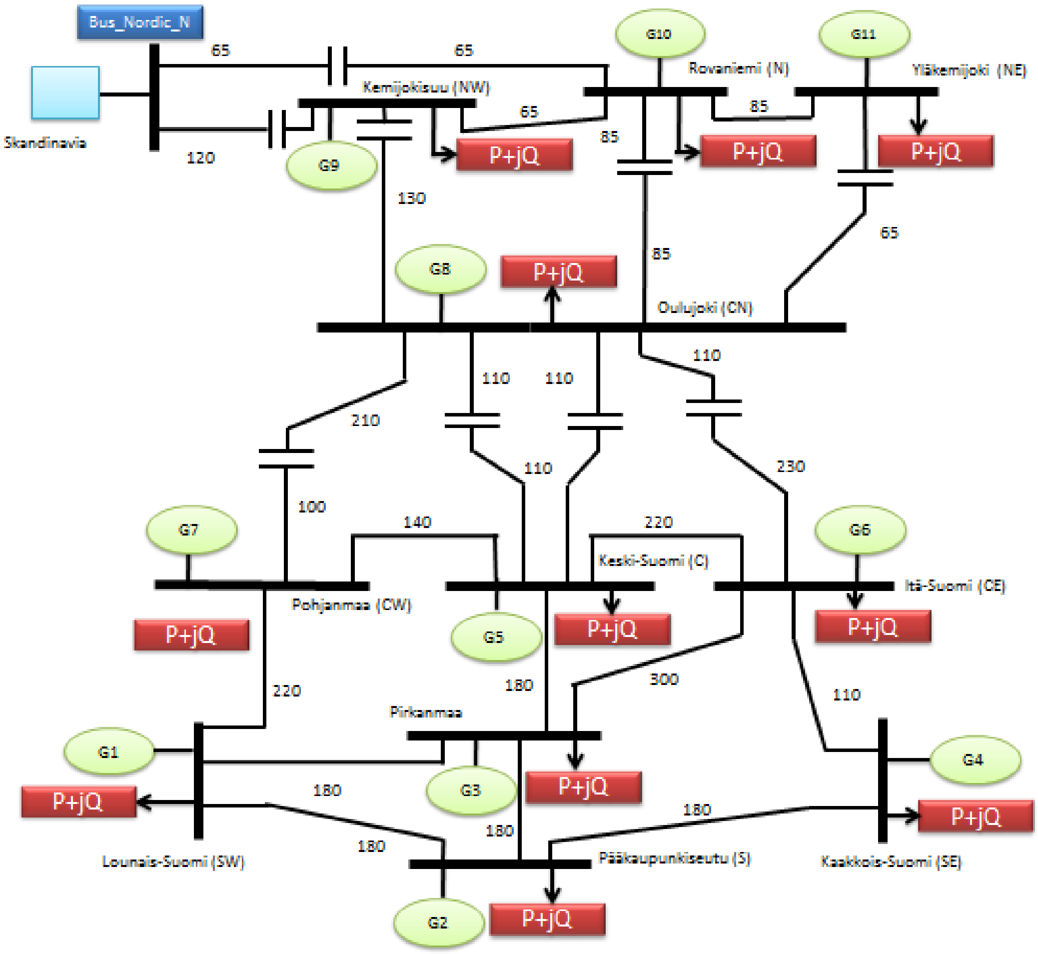

Figure 3.2: Siirtoverkkomalli and Scandinavia network structure

The generation of the complete system is modelled with 15 generators i.e. 11 synchronous generators in Siirtoverkkomalli area and 4 synchronous generators in Nordic32 area. The load case used for this model is low load situation. Generators and associated parameters are attached in Appendix-A. The 5th order model of generator for governor based generations and 6th order model for constant torque of synchronous generator has been chosen for this modelling.

Hydro and Steam based turbine governor model is used in this model. The electrical part of the 6 machines in North of Siirtoverkkomalli area and North of Nordic-32 area is represented by a 5th-order state-space model where mechanical turbine and governor system is used for mechanical torque operation. For South and Central of Siirtoverkkomalli area, the electrical part of the 9 machines is represented by 6th order model and the machines are operating at constant torque mode. The more detailed illustration is depicted in Figure 3.3 where the Scandinavia is shown with its generation characteristics.

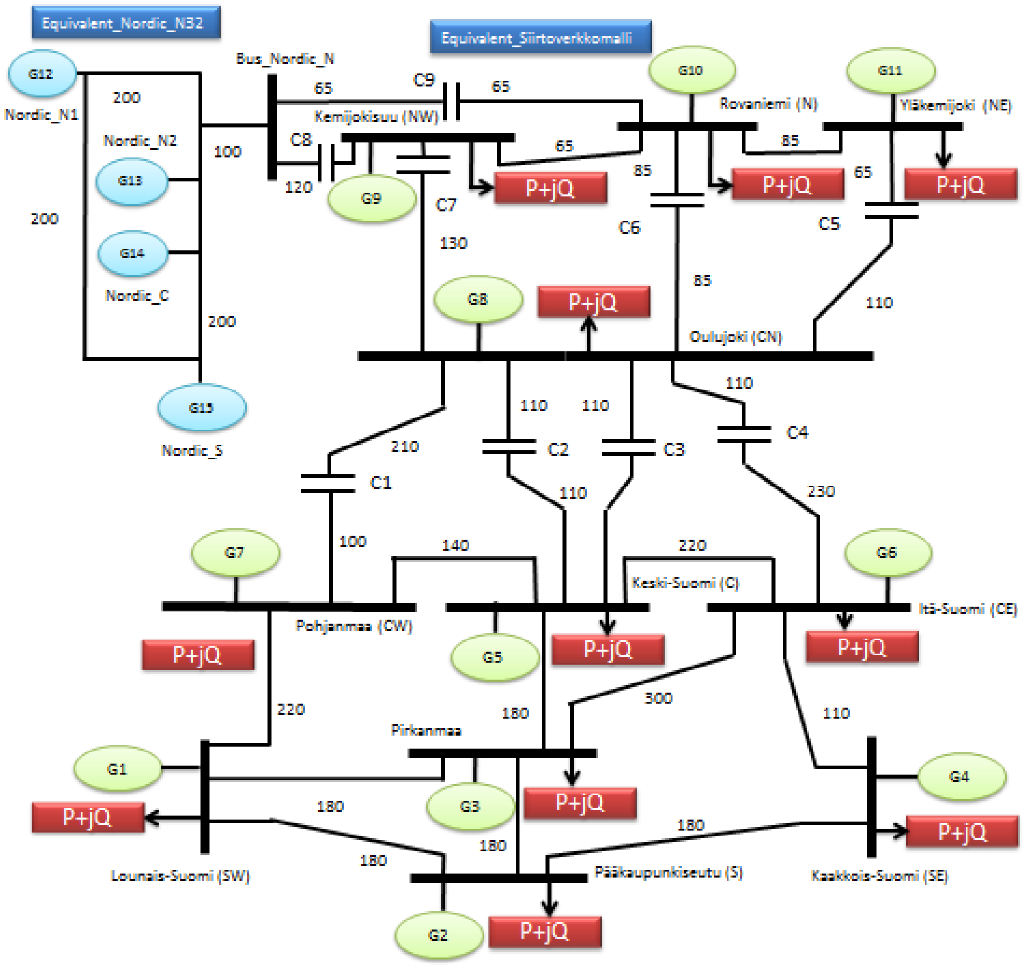

Figure 3.3: Siirtoverkkomalli and Nordic-32 interconnected network structure

3.2 Development and Implementation of the model

As mentioned previously that the equivalent Finnish transmission network model has only been implemented in PSCAD but to finalize the dynamical analysis of the model, it was suggested to develop and implement the model in a different software environment. Therefore, it was agreed to build the model in MATLAB/Simulink because of the sole reason that all the necessary component models and blocks are readily available in SimscapePower Systems^{TM} (formerly SimPowerSystems^{TM}). Henceforth, it is theoretically feasible to implement and simulate the network model utilizing MATLAB/Simulink environment. This section discusses the modelling and dynamic simulation of power systems in MATLAB/Simulink.

3.2.1 Modelling and Dynamic Simulation of Power Systems Network

This part exhibits the different aspects and experiences of power system modelling and dynamic simulation in MATLAB/Simulink. In this thesis project, two systems of different scale are modelled and tested. In future, these models will be used for analytical study depending upon the requirements for example, network analysis technique, power transfers capability analysis, voltage stability and network stability at different fault conditions. The two system models implemented are as under.

- Fin Grid Siirtoverkkomalli: a generic network model reflecting the structure of Finnish network.

- Nordic 32: the model reflects mainly the characteristics of Swedish transmission network in early 1990s and a benchmark network model for voltage and transient stability analysis

It is worth mentioning here that the two systems are originally developed in a different environment and software. For instance, Siirtoverkkomalli model has been implemented and designed so far only using PSCAD, whereas Nordic 32 power system model was described and implemented in PowerFactory. In this thesis project, the original system models designed in other software are considered and taken reference models.

Initially the most difficult part that was experienced at the start of the modelling was the compatibility issues. With very few differences of the model blocks in both the software, the system simulation may be affected and the results obtained may not be optimized. Therefore, software-to-software authentication is done by diminishing the compatibility issue by parametrizing the blocks in order to get the same response as of the reference system in other software. In addition to this, software-to-software validation is done through the comparison of simulation results from different software. Most importantly, the objective of modelling the system in a different software is to have the same reaction as the reference system.

3.2.1.1 Power System modelling principles

The complexity of electric power system makes the modelling process even more difficult and time consuming. This is the reason why the modelling phase needs to be given special attention. While modelling large power systems the modelling may even get more complex due to large size. In addition to this, the main focus in the modelling is to construct stable and integral models so that they can be utilized and taken as a benchmark system in future analytical studies [70]. Therefore, there are certain requirements and standard principles that are needed to be taken into account while modelling. They are:

1. Determination of the reasons for studying the system under test.

In order to lessen the complexity of the power system, it is necessary at the start of the modelling to be aware of the utility of the test system [70]. In this way, the work load is reduced to a much extent and to neglect significant elements form the system. In this regard, Siirtoverkkomalli (reflection of the Finnish network system) has been designed so that it will be capable to reflect various different aspects of technical performance of transmission network transient stability, frequency variations, phenomena in series compensated network. Henceforth, the system should be modelled with the following specifications and characteristics:

- Generator model block equipped with necessary excitation system models and control unit.
- Network compensating devices model block for example series and shunt capacitors.
- Load characteristics.
- Various control and protection units depending upon the power system characteristics and nature.

2. Appropriate reduction of the system model

Various approaches are widely used for network simplification and reduction. With the increasing size and complexity of modern interconnected power systems, it is imperative to use dynamic equivalents to represent some parts of these systems [70]. Therefore, it is a common practice to represent parts of the system by its equivalent or simplified model.

3. Performing the basic load flow simulation for initialization of the system

In most of the cases power flow solutions is used to exhibit the system status. In order to have a stable system and optimized results, the parameters must be clearly defined for the initialization process.

4. Configuring the system to be succinct and minimized

While modelling large power systems, it is of prime importance that the model should be made compact to easily counter the complexity caused by the large network. The whole model comprising of large number of generator buses and load buses and placing the fault in any area disturbs the stability of the system. Thus, for the sake of counter checking the system configuration must be concise as far as possible [70].

5. Correct parametrization of the system model

In order for the solver of the software to operate efficiently and effectively, parametrization of the model should be done with great care [70]. As a result, the simulation results will be desired.

Besides all the above principles of power system modelling, there are few important and useful tips and steps that may make things easy while modelling. They are:

- Reading the system description and all the available parameters.
- Availability of the exact component models as of the reference system.
- Determination of the parameters and data.
- Implementing the model in MATLAB/Simulink.
- Initialization and load flow simulation of the system model.
- Simulating the model, analyzing the results for the authenticity.

3.2.2 Model and Data

1. **Buses:**
   The overall system consists of 33 node buses, 11 of which are generator buses whereas 11 load buses. The system operates at various voltage levels. The transmission buses operates at 400kV, generator buses at 26kV and 110kV for load buses. The model diagram of generator and load bus connected to node is shown in Figure 3.4. as under.

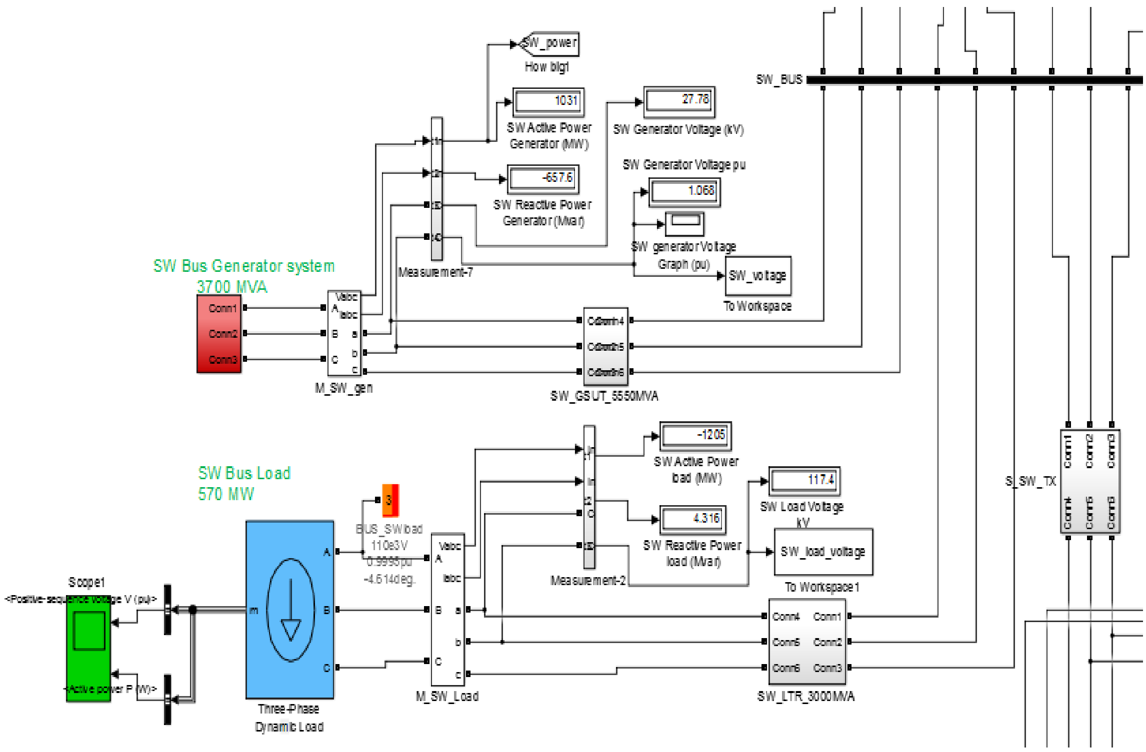

Figure 3.4: Generator and Load bus connected to a node.

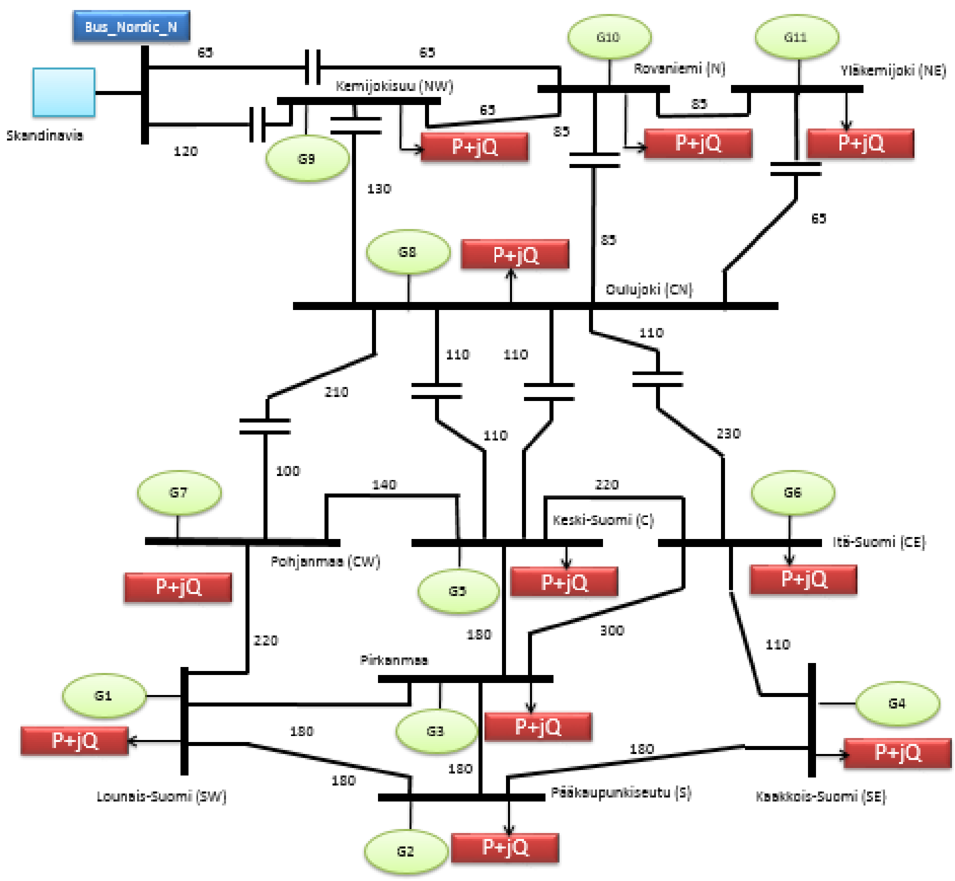

Figure 3.5: Siirtoverkkomalli network structure system

2. Transmission Lines:

The system has been modelled by 21 transmission lines. The block is modelled by using a three phase PI- equivalent circuit. The parameters used are illustrated in the Figure 3.6 below. The positive and zero sequence values are used for resistance, inductance and capacitance and are represented in Ohms/km, H/km and F/km respectively.

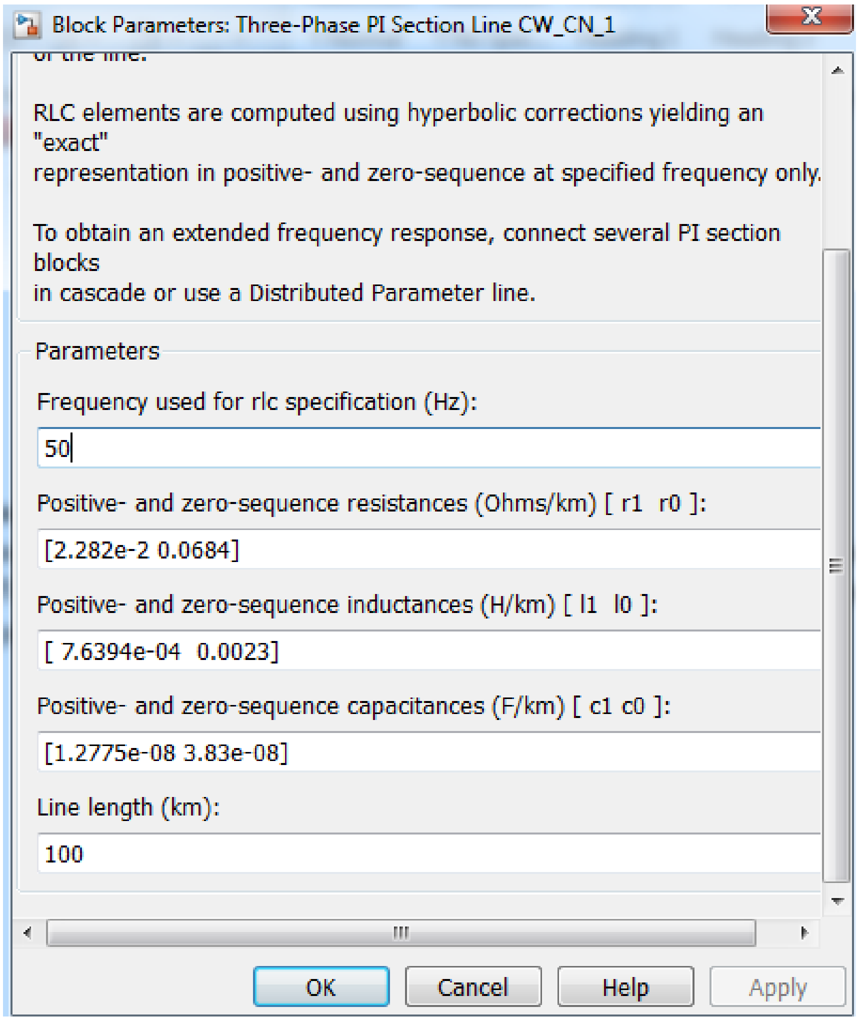

Figure 3.6. PI- equivalent circuit parameters

3. Loads:

For the load flow calculation to converge, it is important to define the type of load to be used. There are three different types of load; constant Z, constant PQ and constant I. The loads in Siirtoverkkomalli are modelled using constant impedance “Z” type. In the initialization of the model, the solver of the software does the transformation into constant impedances R_l and X_l by the following equations:

$$P_0 = \frac{R_l U_0^2}{R_l^2 + X_l^2}, \; Q_0 = \frac{X_l U_0^2}{R_l^2 + X_l^2}$$

(3.1)

Where U_0 : voltage magnitude of the node

P_0 : load active power

Q_0 : load reactive power

4. Shunt Load Reactors:

The system has 11 shunt load reactors in use. In MATLAB/Simulink it is represented by three phase RLC branch as depicted in the Figure 3.7.

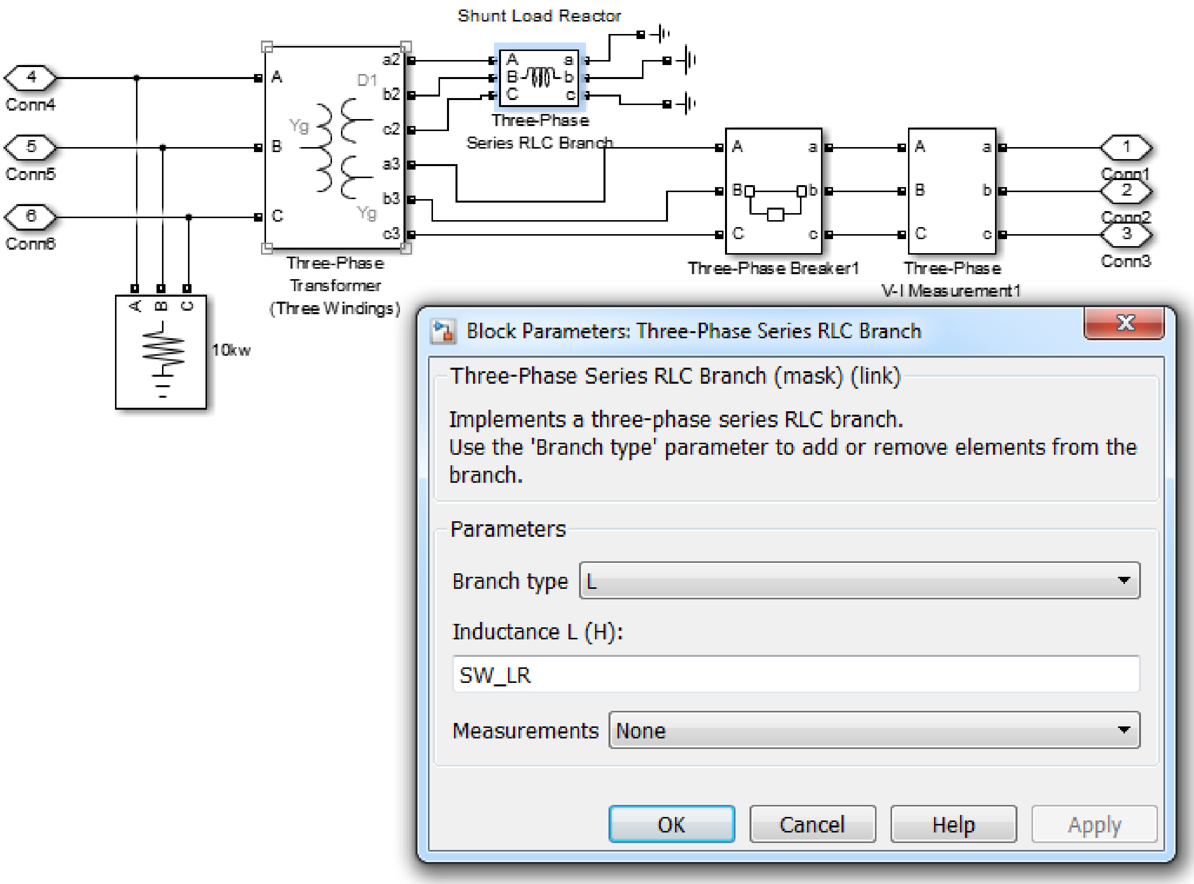

Figure 3.7: Shunt reactor model with parameter window displayed

5. Synchronous generators:

Modelling of the synchronous generators is accomplished by two different synchronous generator models. Round rotor machines for nuclear and steam power plants (Order VI) modelled in the dq reference frame while salient pole synchronous machines for hydro power plants (Order V) also modelled in the dq reference frame. Synchronous generator modelled in MATLAB/Simulink is shown in following Figure 3.8. All the data follows system description provided by Fin Grid Oy. Generators and associated parameters are attached in Appendix- A.

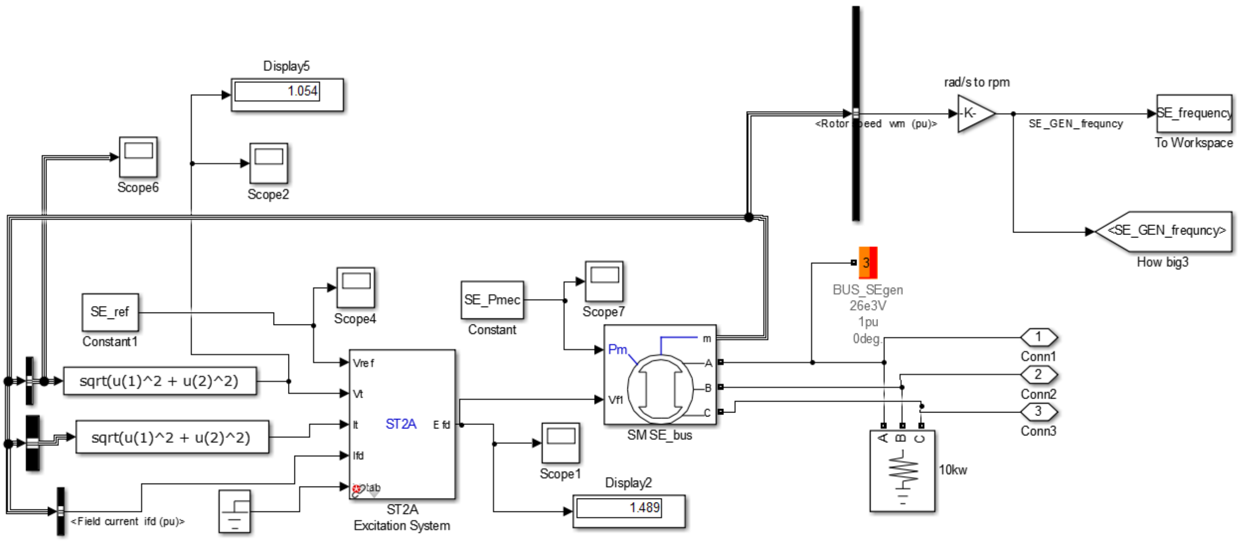

Figure 3.8: Functional block diagram of synchronous machine excitation control system

6. Turbine and Governor system:

For the mechanical torque operation, mechanical turbine and governor system model is used in the network. The model is depicted in Figure 3.9.

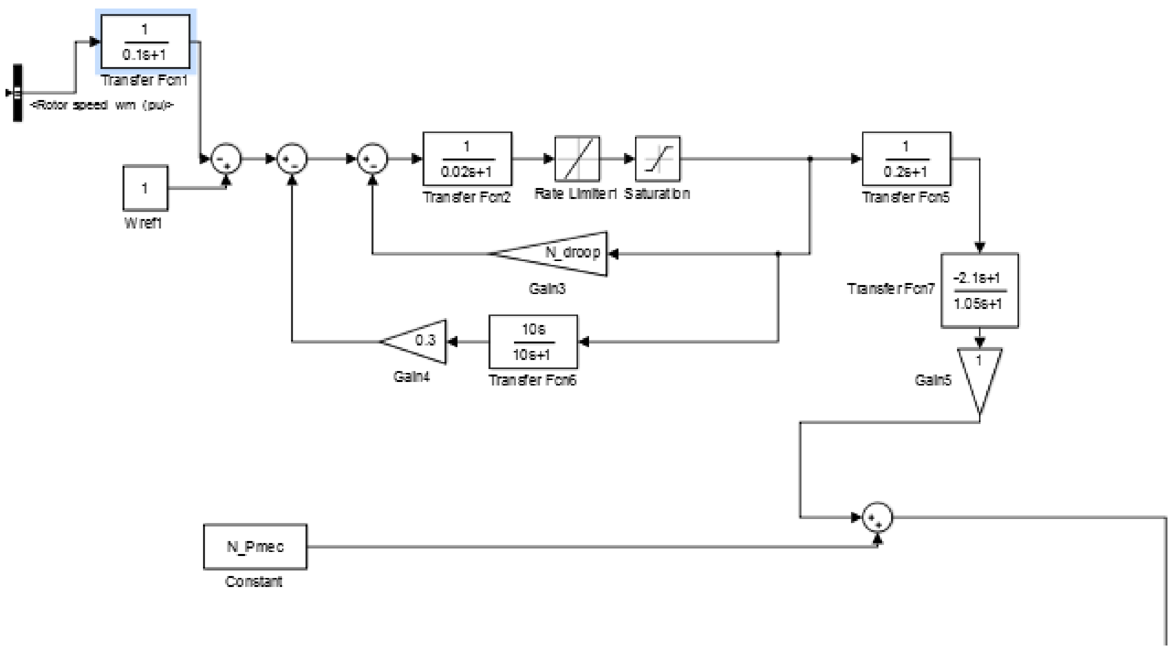

Figure 3.9: Turbine governor model

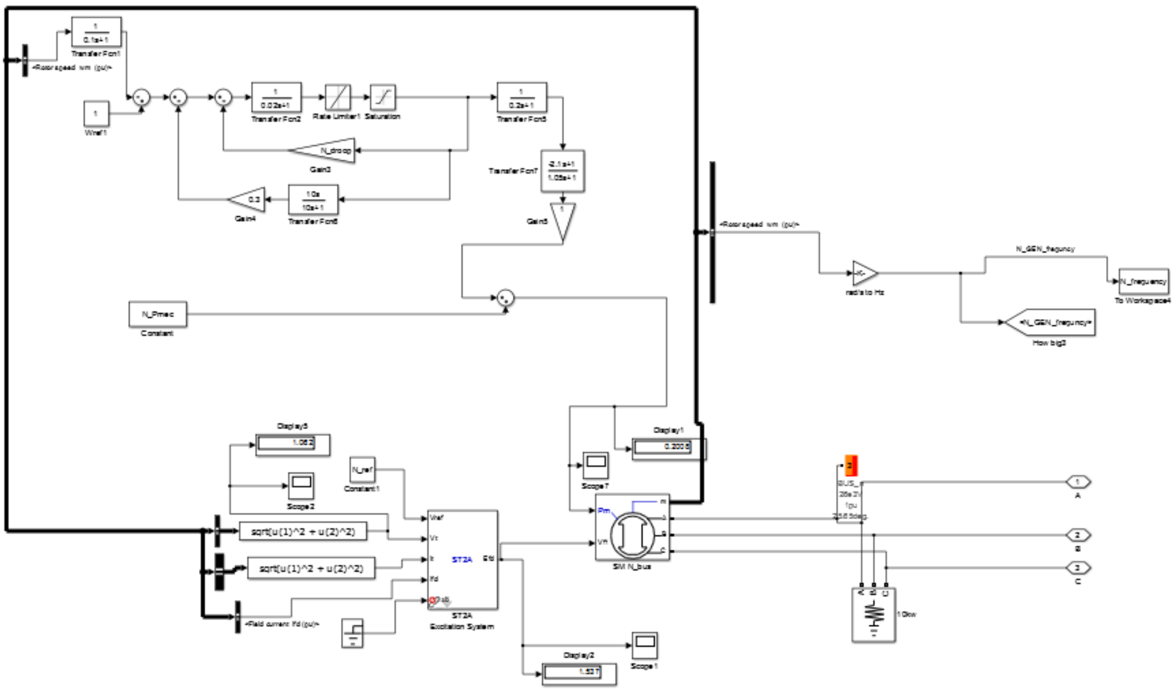

Figure 3.10: Functional block diagram of synchronous machine excitation with Turbine and Governor control system

3.3 Simulation and Validation

The next step of this study is to analyze the system's dynamic behavior. For this purpose, MATLAB/Simulink provides the possibility of simulating the system to investigate the dynamic response of the system.

Different tests have been conducted to analyze the power transfer capability and network stability at fault conditions. These are:

a) Three-phase-to-ground fault at different location.
b) Loss of line.
c) Increased electrical length by 100 %.

The next step is to create the import and export cases in order to analyze the stability and robustness of the system in the presence of network disturbances. Therefore, following load flow cases were conducted:

1. Case-1: Zero power flow case
2. Case-2: 600MW Export case (South-North), (Stable case)
3. Case-3: 600MW Import case (North-South), (Stable case)
4. Case-4: 1100MW Export case (South-North), (Unstable Case)
5. Case-5: 1200MW Import case (Nordic-South), (Stable Case)

6. Case-6: 1400MW Import case (Nordic-South), (Unstable Case)

1. Case-1: Zero power flow case

The objective of the power flow study is to validate the fact that whether the model is capable to reflect various different aspects of technical performance of transmission network i.e. transient stability, frequency variations and voltage stability. The first case studied is the zero power flow case (almost zero power flows throughout the bus). Local generators are there to fulfill the local load demand. A three-phase-to-ground fault has been applied at ‘Rovaniemi (N)’ bus for 10ms.

The ensuing frequency and voltage behavior are shown in Figure 3.11(a),3.11(b),3.11(c),3.11(d). It is observed from these results that the system under the three-phase-fault test is stable. All the voltages are close the nominal and there are no dominant frequency fluctuations in the system. Since the system is stable therefore there is no need for compensation devices to be installed. After a thorough study, it is concluded that zero power flow case is the pretty much close to the ideality in terms of efficiency of the network, stability of the network and economy point of view.

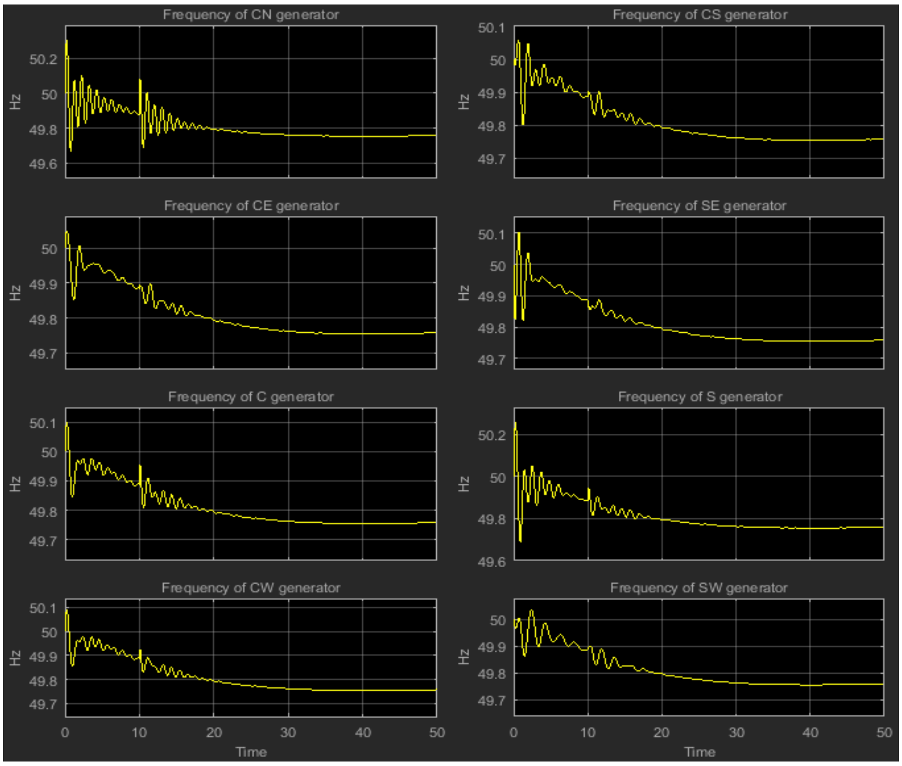

Figure 3.11(a): Frequency of Central and South region generators under 3-phase-ground fault

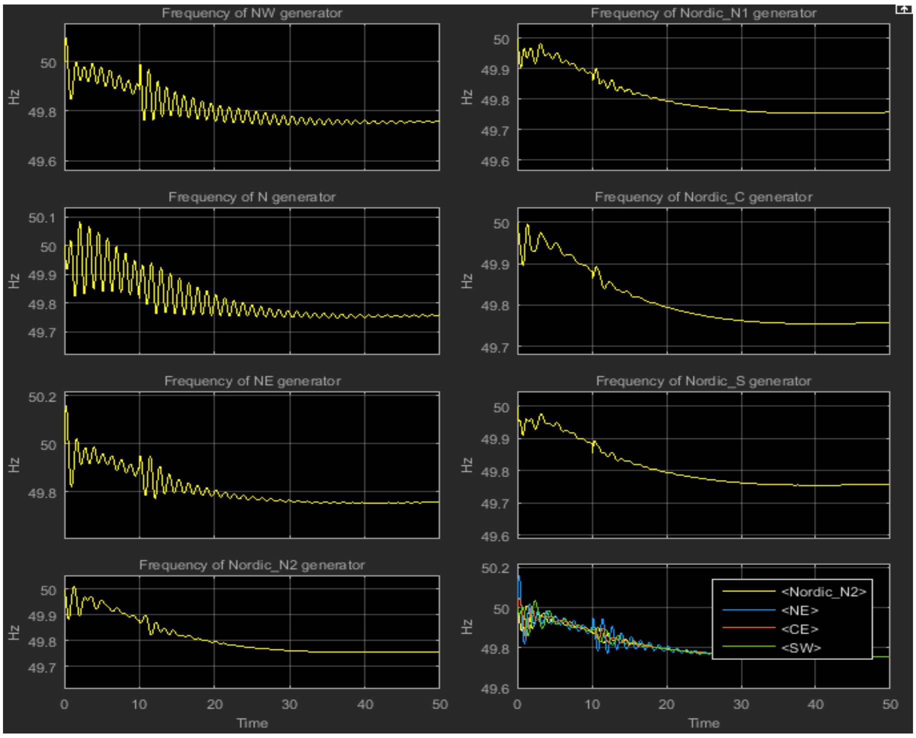

Figure 3.11(b): Frequency of North and Nordic region generators under 3-phase-ground fault

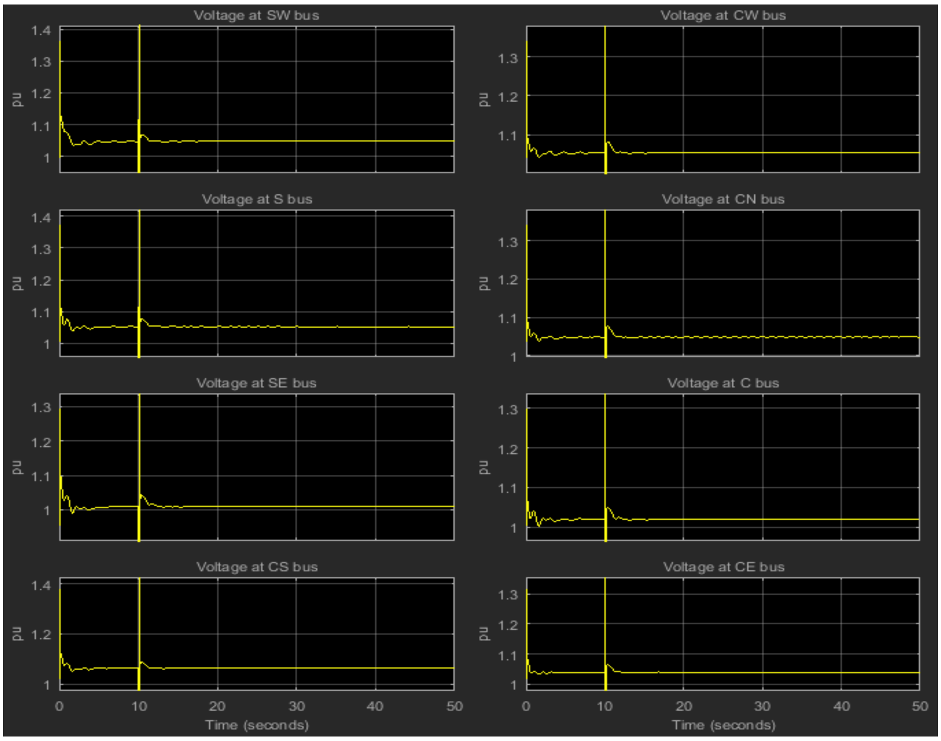

Figure 3.11(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault

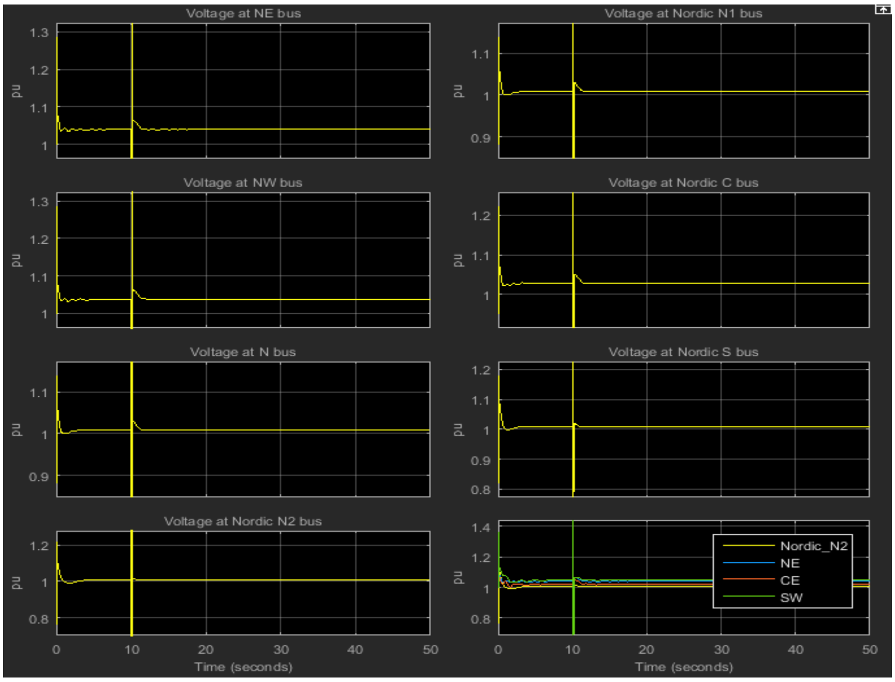

Figure 3.11(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault

2. Case-2: 600MW Export case (South-North), (Stable case)

In this test case, 600MW of power flow is created and the system is analyzed after testing few three-phase-to-ground fault and loss of line at different locations of the network. The fault location selected in this test case is Lounais-Suomi (SW) and Kemijokissu (NW). The ensuing frequency and voltage behavior is depicted in Figure 3.12(a),3.12(c),3.12(d).

<u>When fault is at Lounais-Suomi (SW)</u>

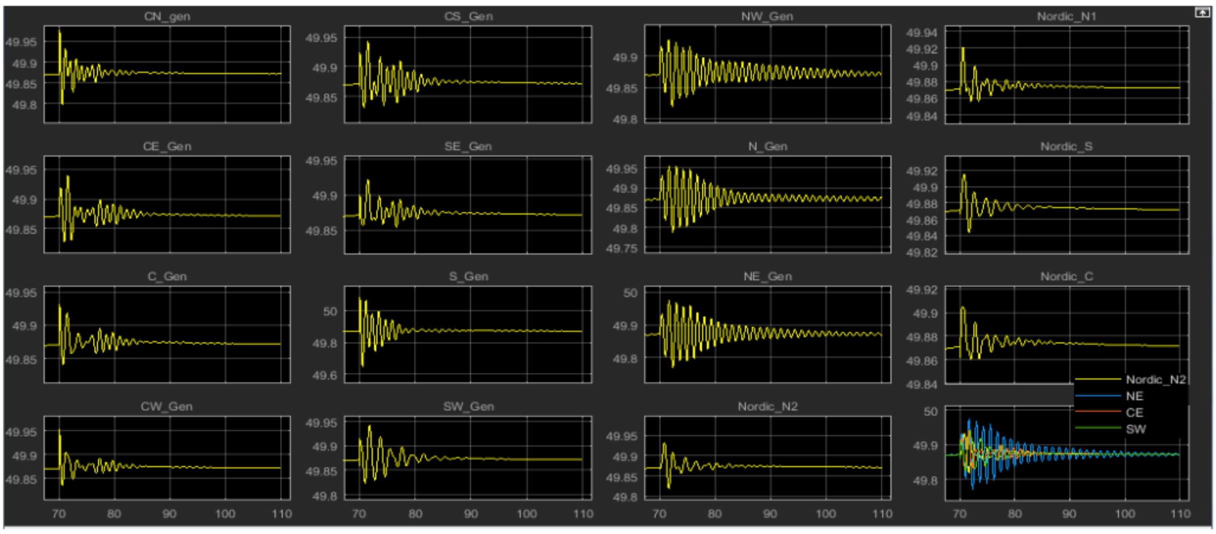

Figure 3.12(a): Frequency of generators under 3-phase-ground fault is at SW bus, 600MW (Stable case)

It can be seen from these results that the application of fault at SW bus for 100ms, enhanced weak damping is visible in the Northern region and frequency stabilizes below 49.9 Hz in all regions. In addition to this, the block diagram of power flow from South to North and North to Nordic region is also shown in Figure 3.12(b)

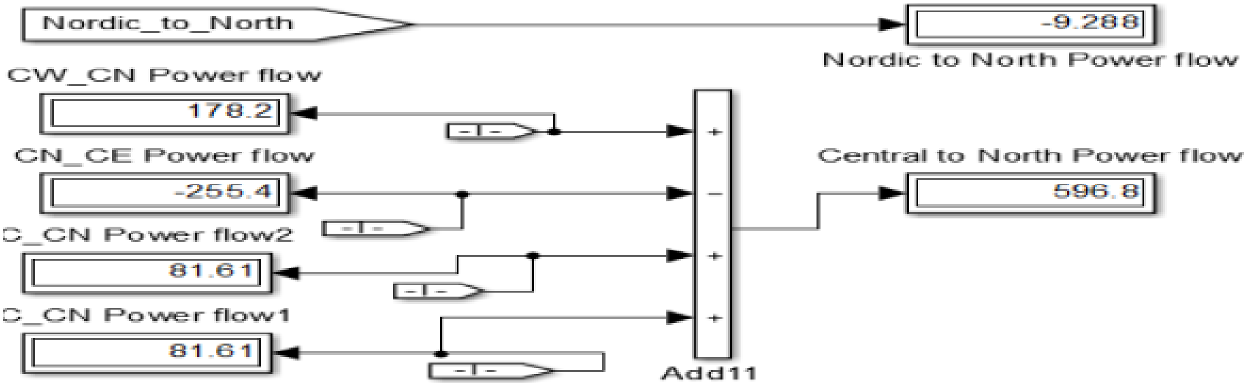

Figure 3.12(b): Block diagram of power flow from South to North and North to Nordic

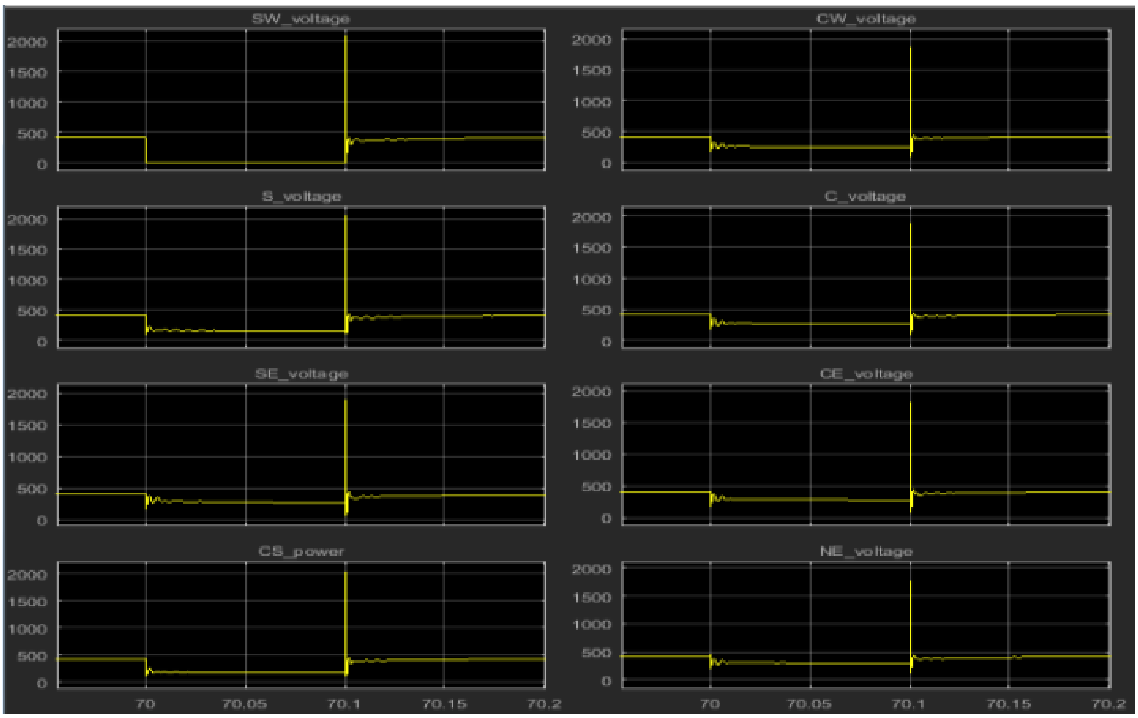

Figure 3.12(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault is at SW bus

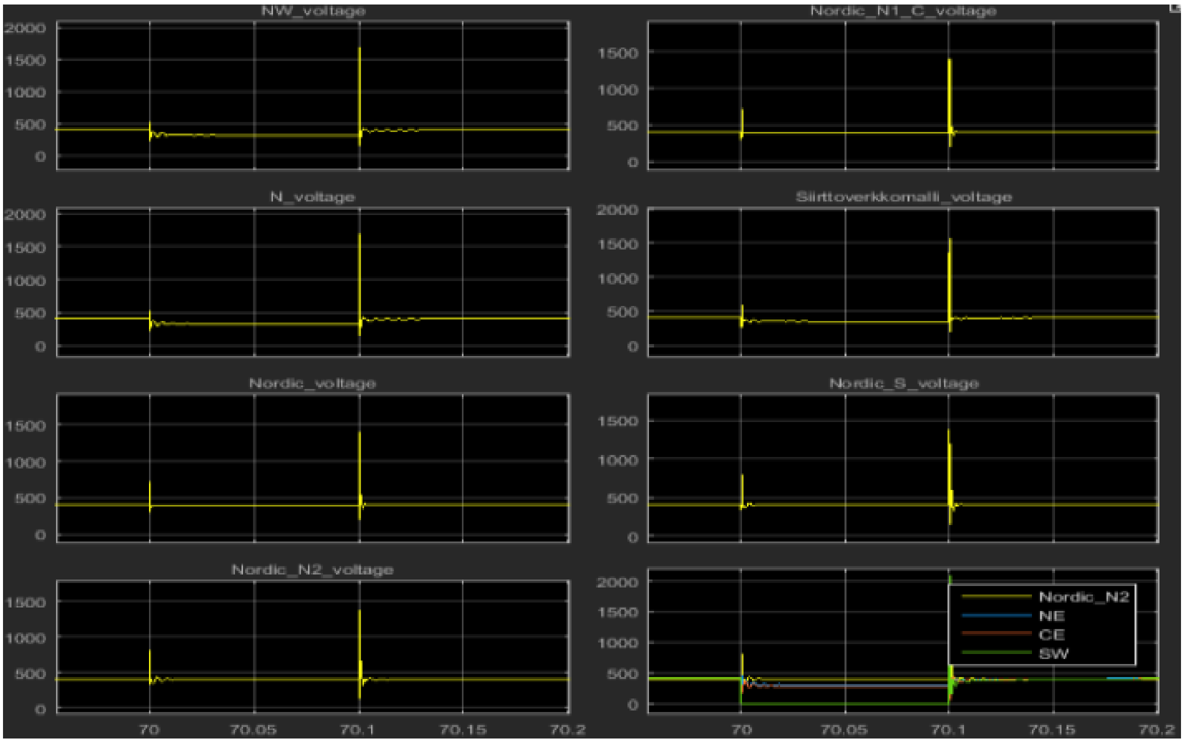

Figure 3.12(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault at SW bus

When fault is at Kemijokissu (NW bus)

The frequency and voltage graphs are illustrated in the Figure 3.13(a), 3.13(c), 3.13(d).

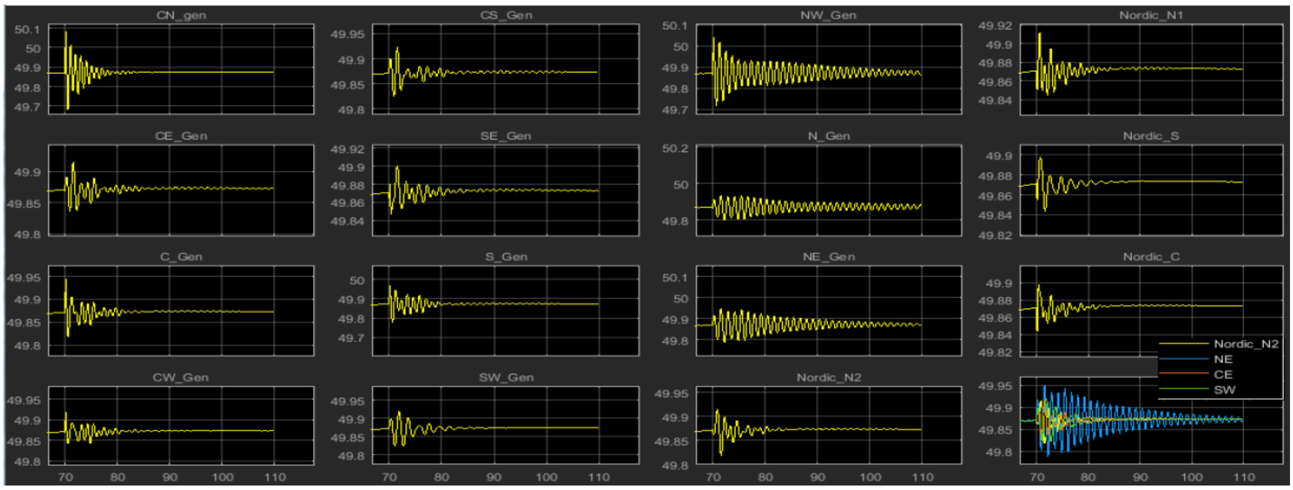

Figure 3.13(a): Frequency of generators under the under 3-phase-ground fault at NW bus, 600MW (Stable case)

In this test case the fault is at NW bus for 100ms. It is observed that weak damping is visible in the NW, CN, NE and N generators terminal. Frequency stabilizes below 49.9 Hz in the central and nordic regions. The power flow through buses from South to North and Nordic to North is shown in the Figure 3.13(b) as under.

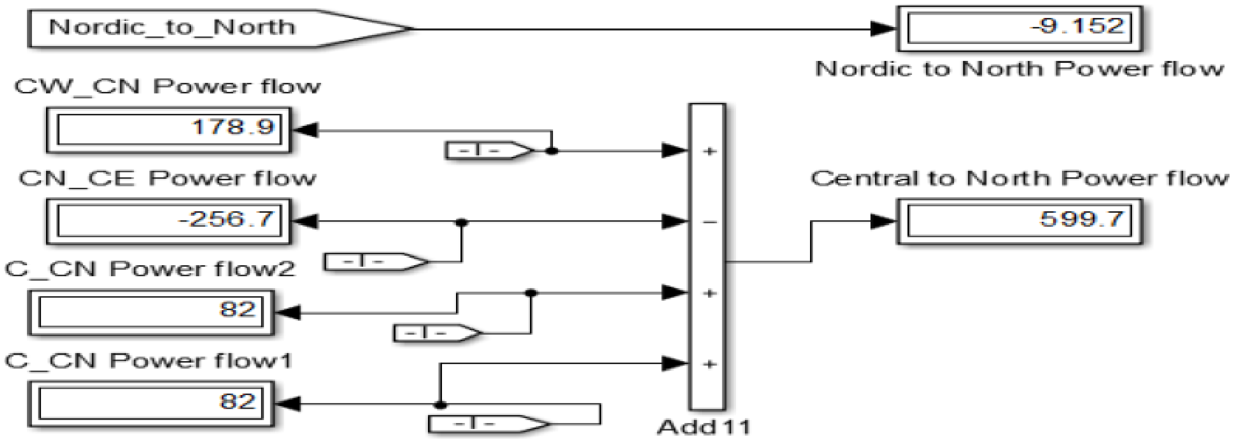

Figure 3.13(b): Block diagram of power flow through buses from South to North and Nordic to North

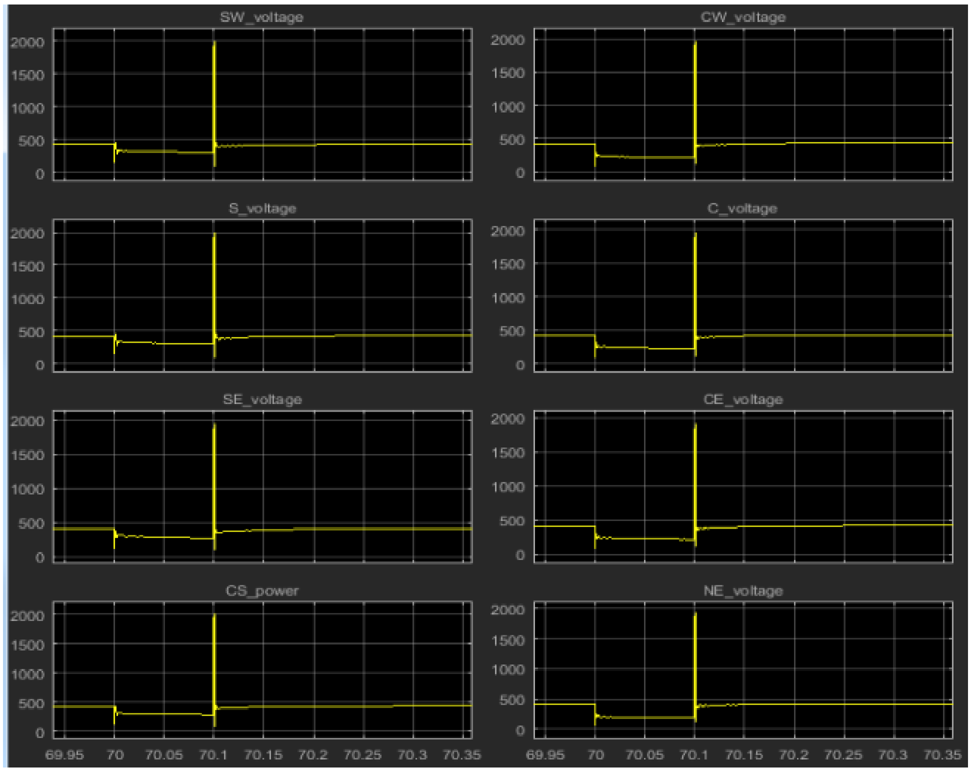

Figure 3.13(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault at NW bus

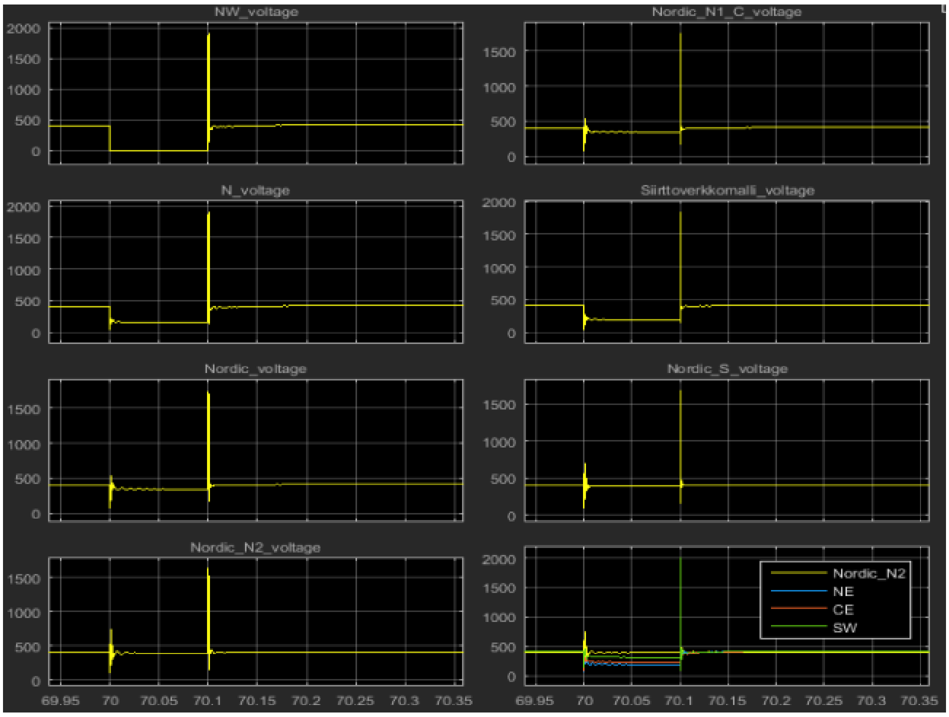

Figure 3.13(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault at NW bus

<u>When fault is at Lounais-Suomi (SW bus, 100ms) and loss of line between Pohjanmaa(CW) and Oulujok(CN)</u>

After the following tests conducted, it is summarized that the overall network performance seems to be rather good. The simulation results compiled are shown in the following Figures 3.14(a),3.14(c),3.14(d). Initially the frequency goes up right after the fault and after a certain time of the simulation run the frequency stabilizes at 49.9 Hz. On the other hand, all the voltages at 400kV North, Nordic, South and Central regions buses under the three-phase-to-ground fault are close to the nominal value. Hence the system is stable.

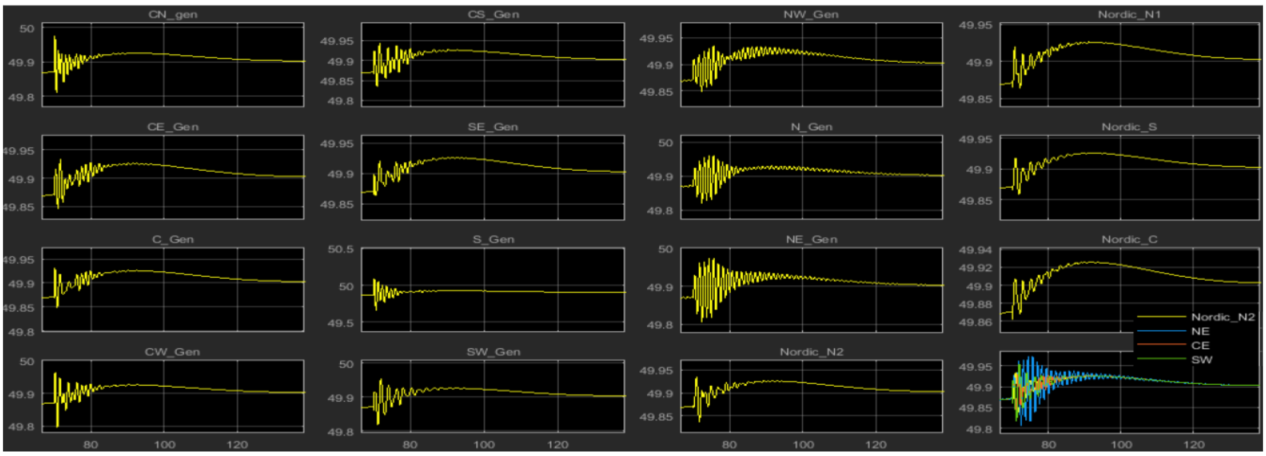

Figure 3.14(a): Frequency of generators under the under 3-phase-ground fault at Lounais-Suomi, 600MW (Stable case)

The following Figure 3.14(b) contains the information of the power flow from one region of the network to another.

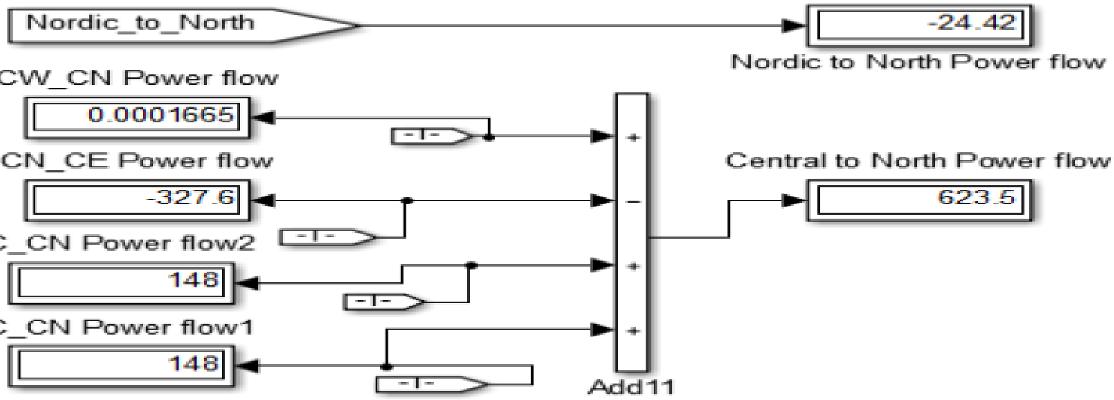

Figure 3.14(b): Block diagram of power flow through buses from South to North and Nordic to North

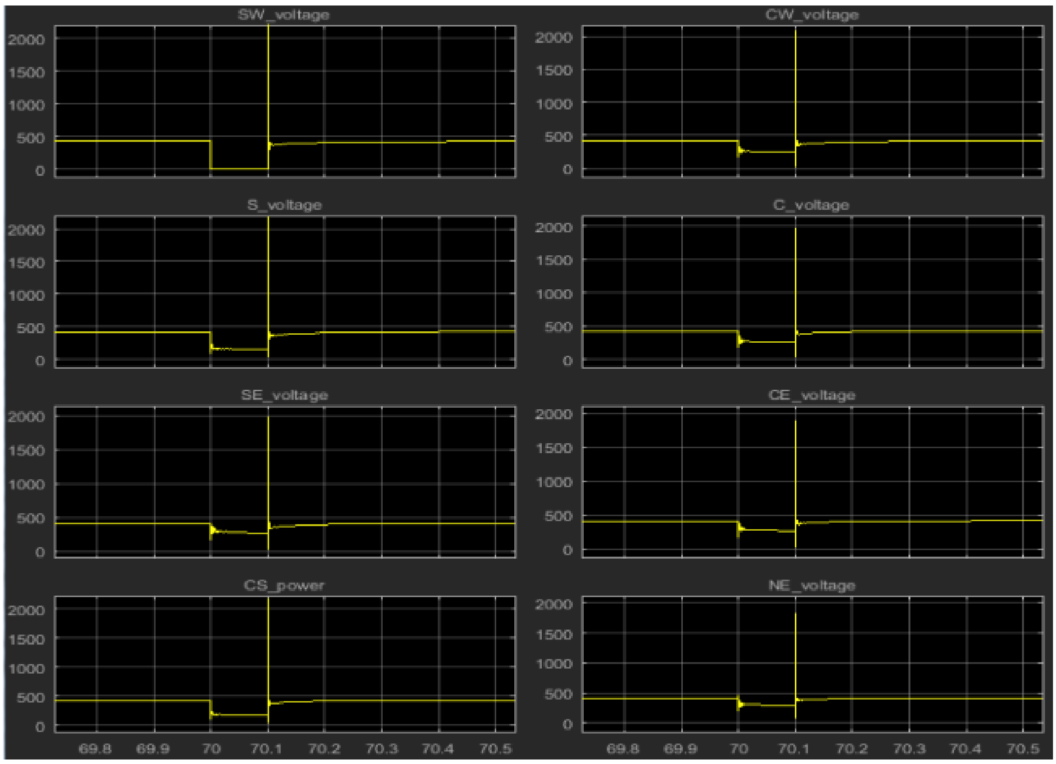

Figure 3.14(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault at Lounais-Suomi

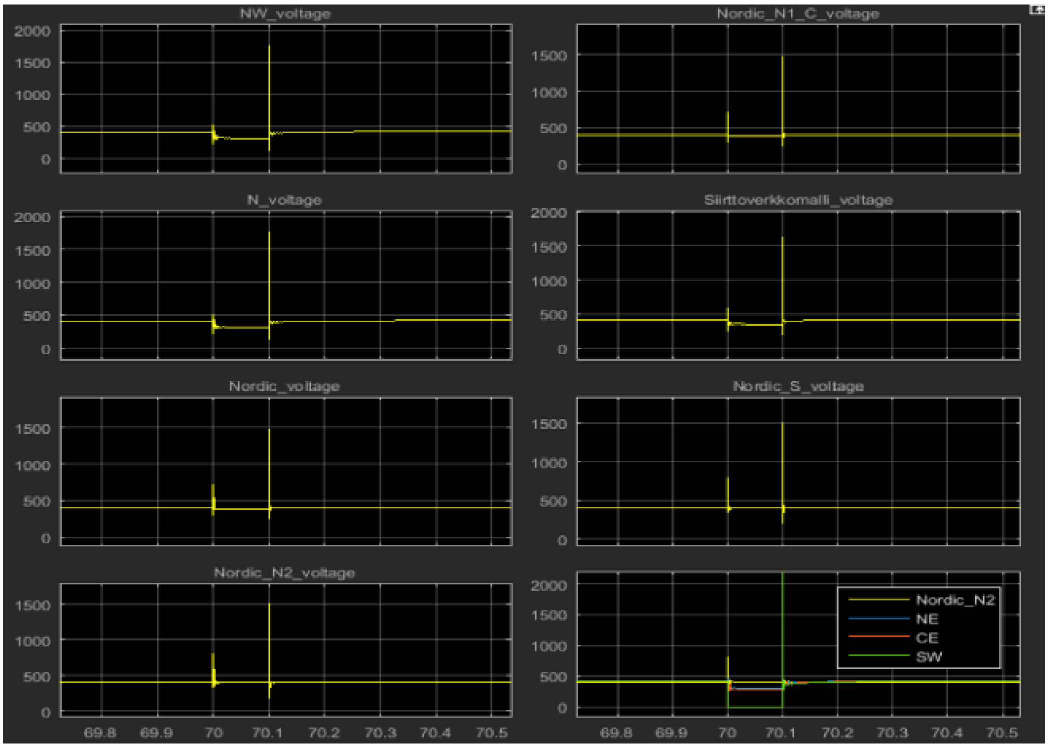

Figure 3.14(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault Lounais-Suomi

<u>When fault is at Kemijokisuu (NW bus, 100ms) and loss of line between Pohjanmaa(CW) and Oulujok(CN)</u>

The system performance under different tests can be clearly seen from the following Figures 13.15(a), 13.15(b), 13.15(c), 13.15(d). The system stabilizes and there is no need of compensation devices to be installed.

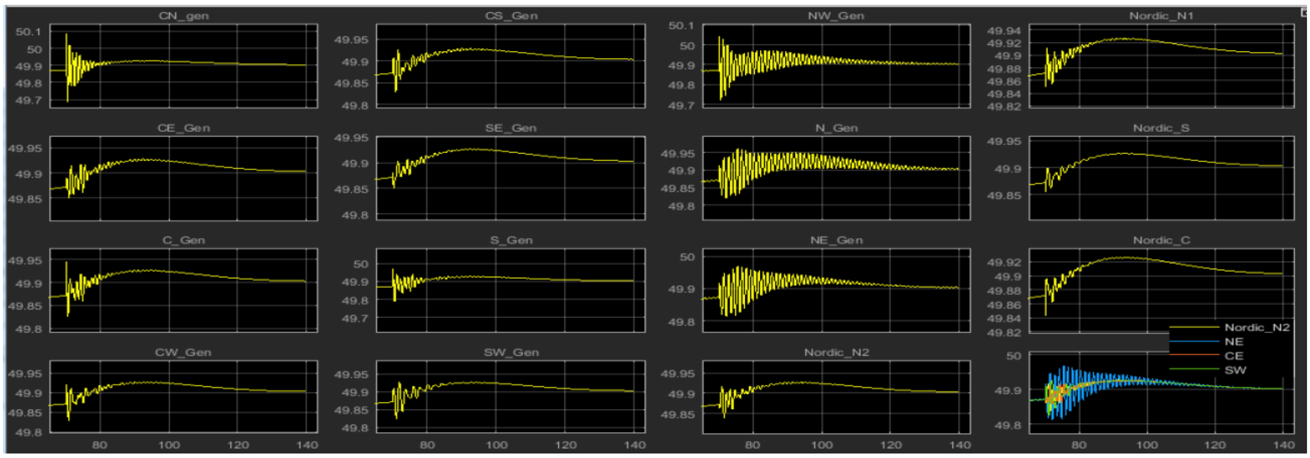

Figure 3.15(a): Frequency of generators under the under 3-phase-ground fault at NW, 600MW (Stable case)

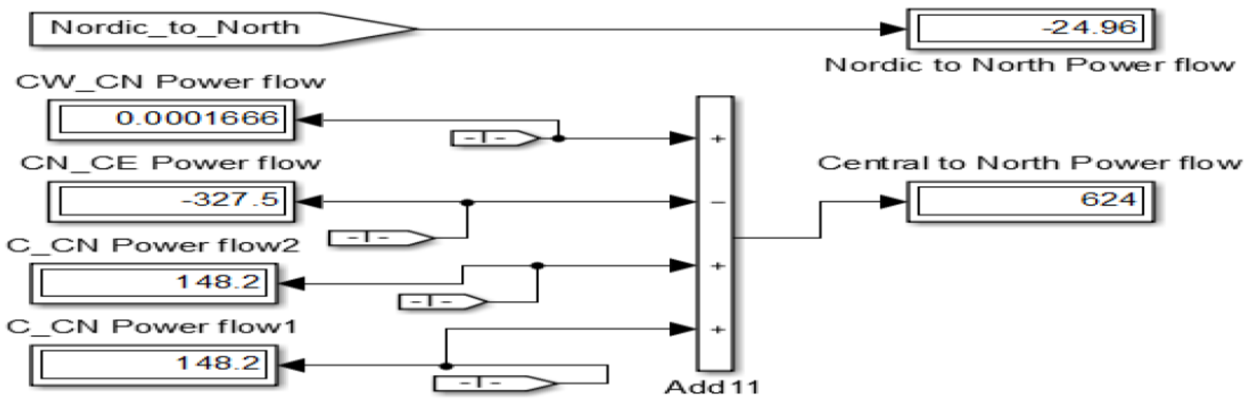

Figure 3.15(b): Block diagram of power flow through buses from South to North and Nordic to North

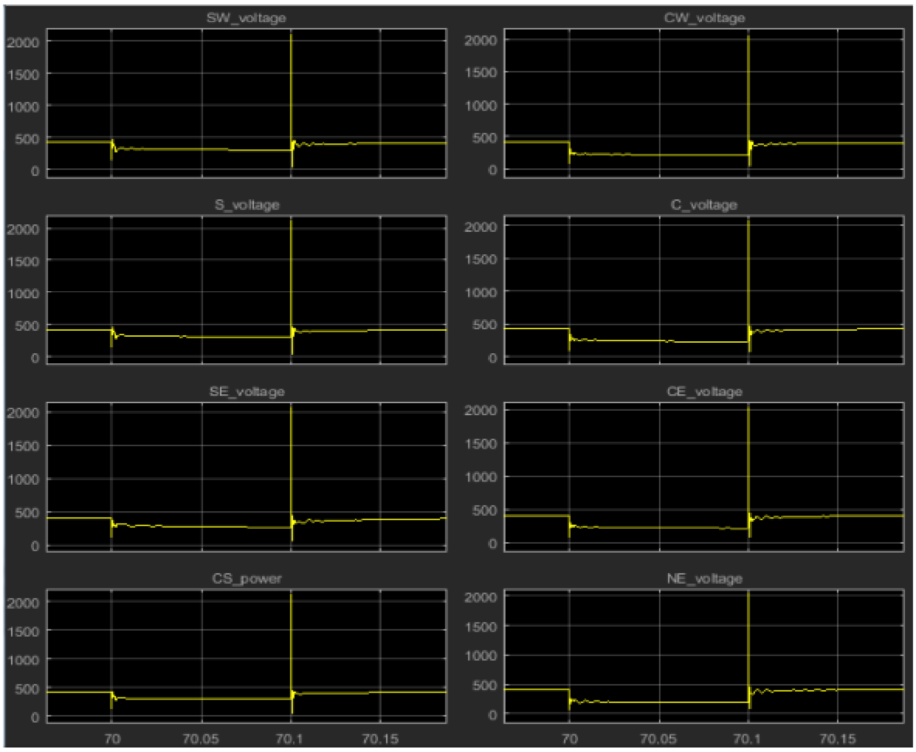

Figure 3.15(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault at NW bus

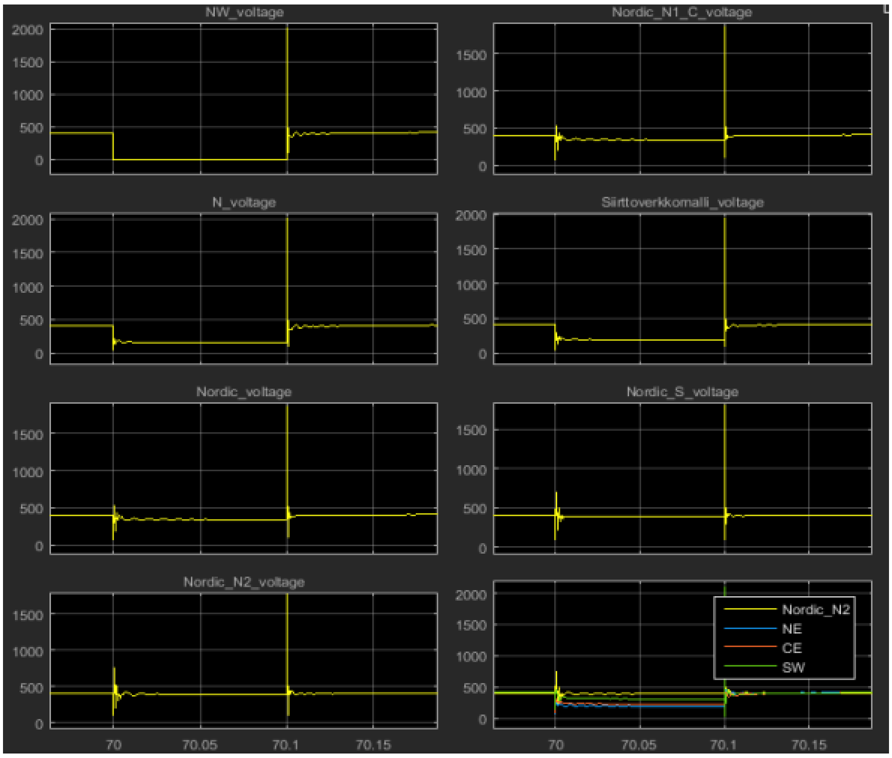

Figure 3.15(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault at NW bus

3. Case-3: 600MW Import case (North-South), (Stable case)

<u>When fault is at Lounais-Suomi (SW bus, 100ms) and loss of line between Pohjanmaa(CW) and Oulujok(CN)</u>

Loss of line after the fault causes the sudden rise in the frequency slightly above 49.9 Hz. Weak damping is visible in the NW, N, NE generators. The overall network performance is pretty much acceptable as per the simulation results. The study is conducted with the help of frequency and voltage support study and the results obtained are shown in Figures 3.16(a),3.16(b), 3.16(c), 3.16(d).

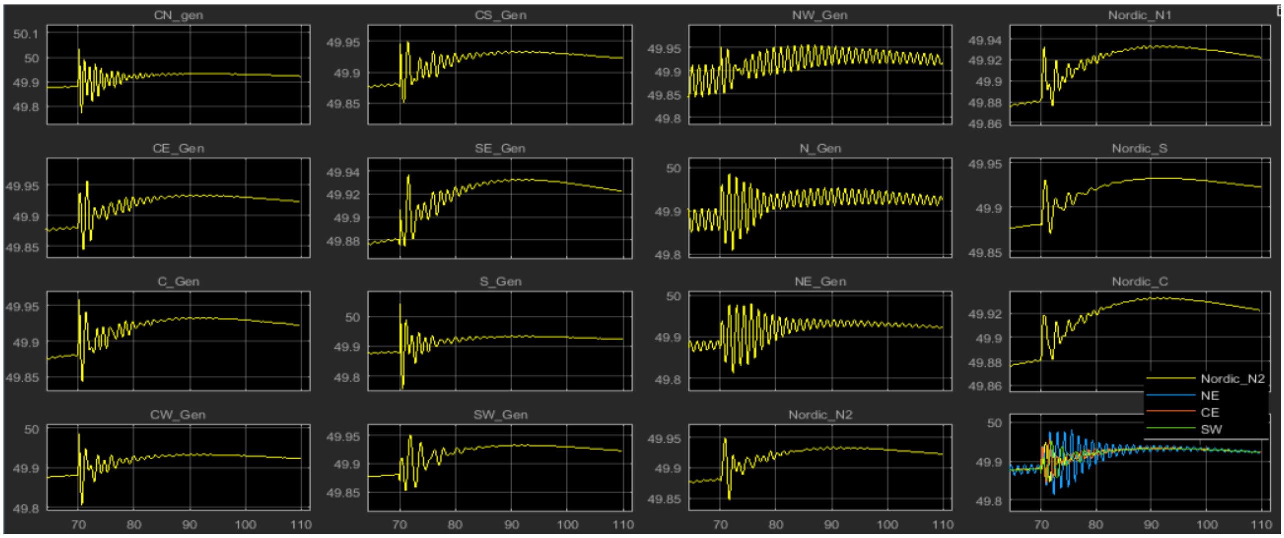

Figure 3.16(a): Frequency of generators under the under 3-phase-ground fault, 600MW Import case (Stable case)

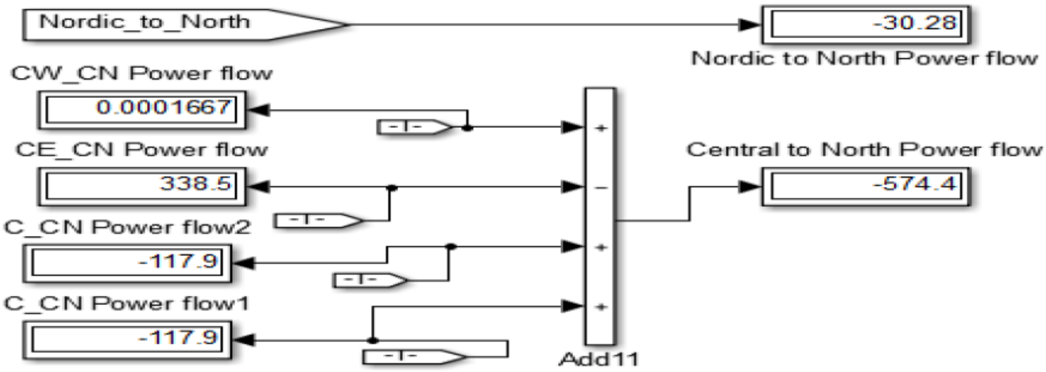

Figure 3.16(b): Block diagram of power flow through buses from South to North and Nordic to North

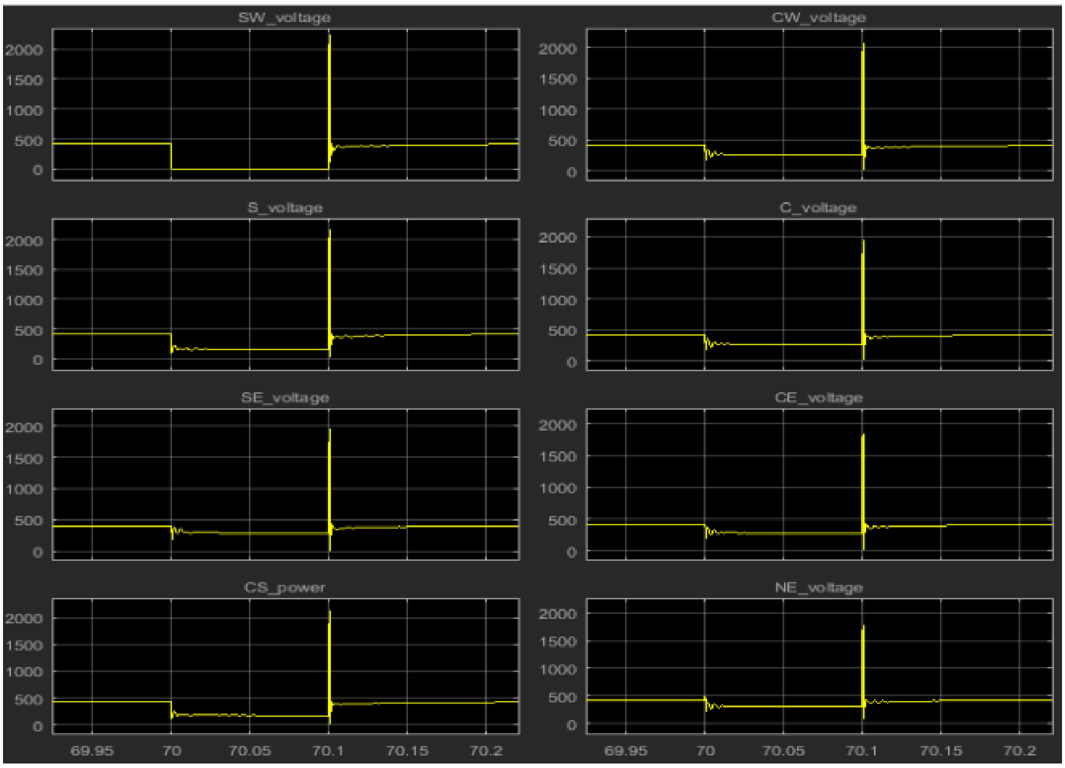

Figure 3.16(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault

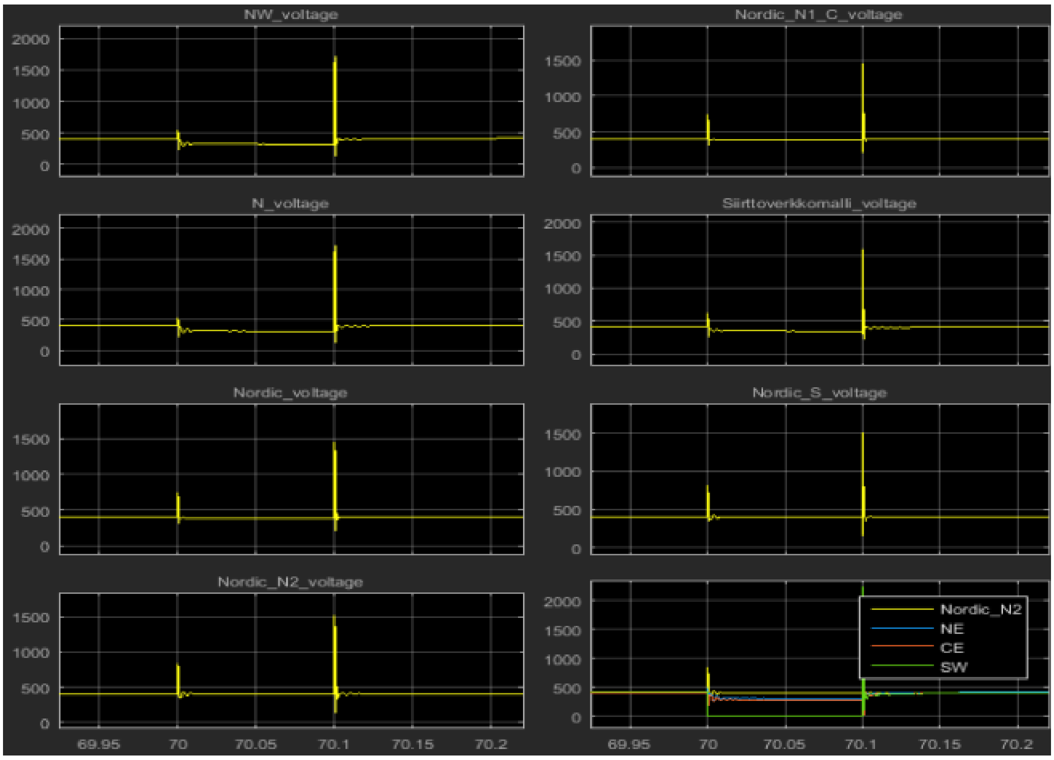

Figure 3.16(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault

<u>When fault is at Kemijokisuu (NW bus, 100ms) and loss of line between Pohjanmaa(CW) and Oulujok(CN)</u>

The following discussion has been done after the analysis of the simulation results obtained at the end of the tests conducted. It can be clearly seen that the loss of line after the fault causes a sudden rise in the frequency slightly above 49.9 Hz. However, very weak damping is visible in the NW, N, NE generators and frequency does not stabilize in these generators. Nonetheless, the overall effect is nearly stable since the upper value of one generator is neutralized by the lower value in other generator frequency.

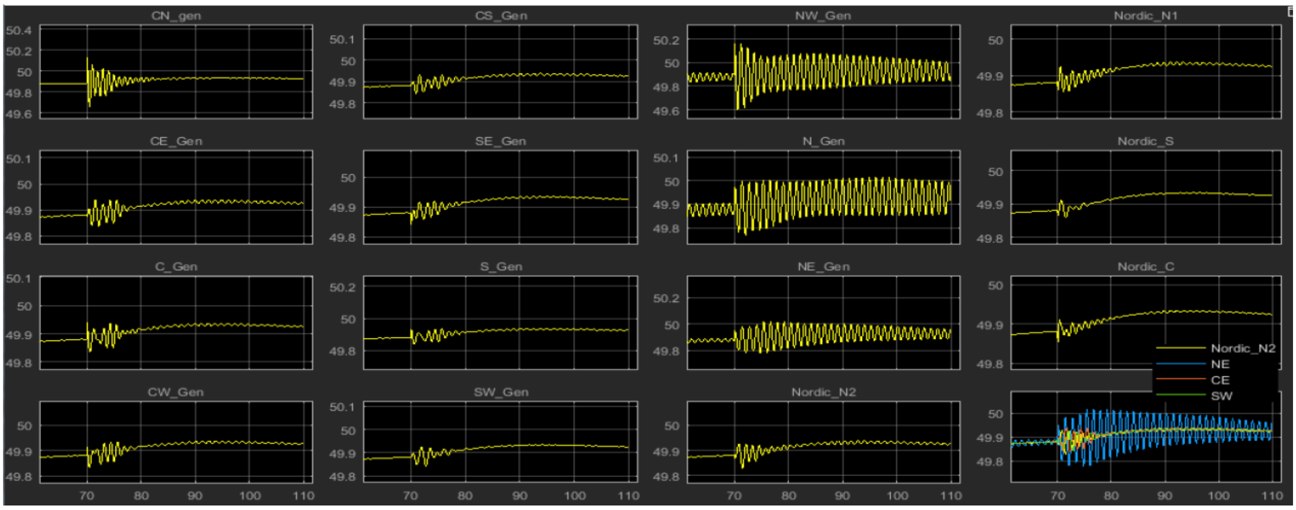

Figure 3.17(a): Frequency of generators under the under 3-phase-ground fault at NW bus, 600MW (Stable case)

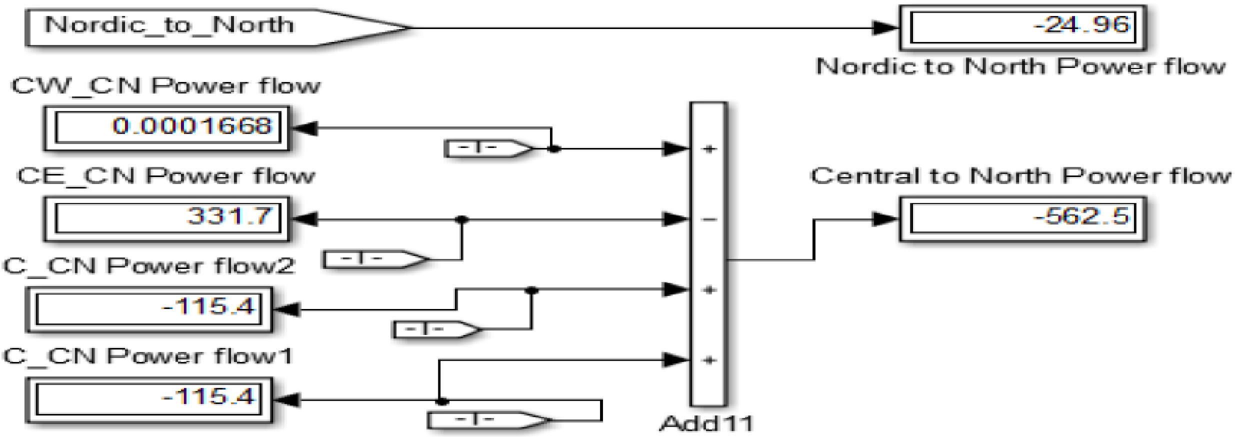

Figure 3.17(b): Block diagram of power flow through buses from South to North and Nordic to North

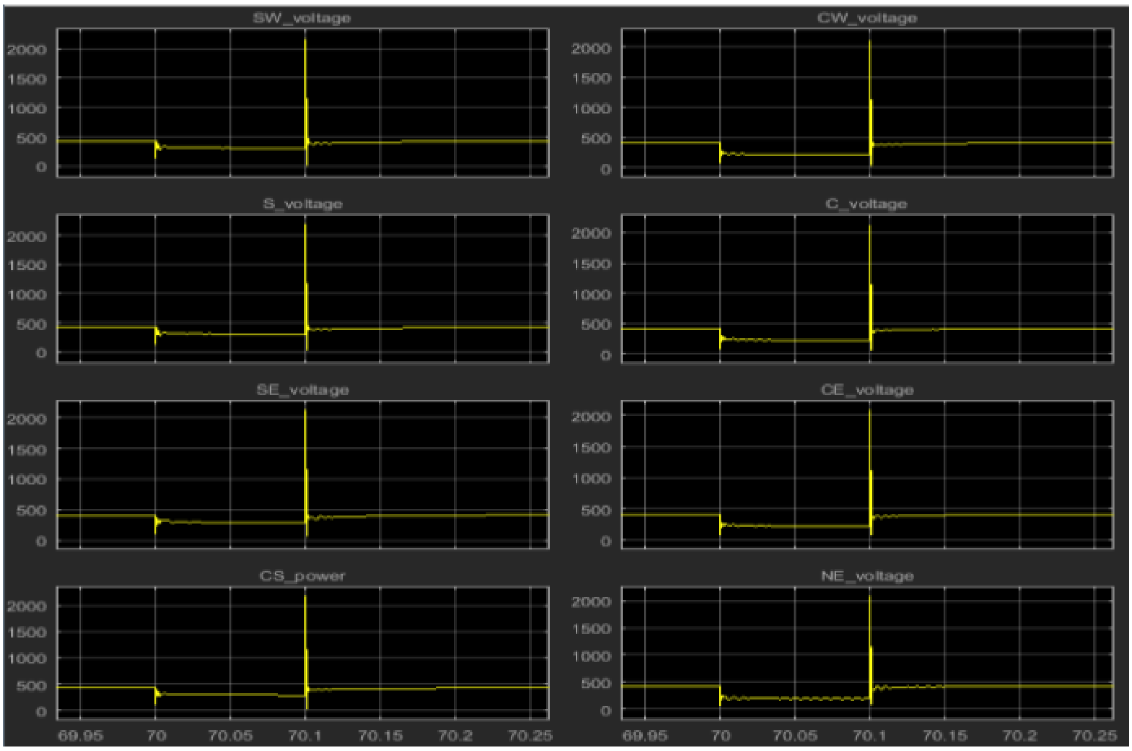

Figure 3.17(c): Voltage at 400kV South and Central region buses under 3-phase-ground fault at NW bus

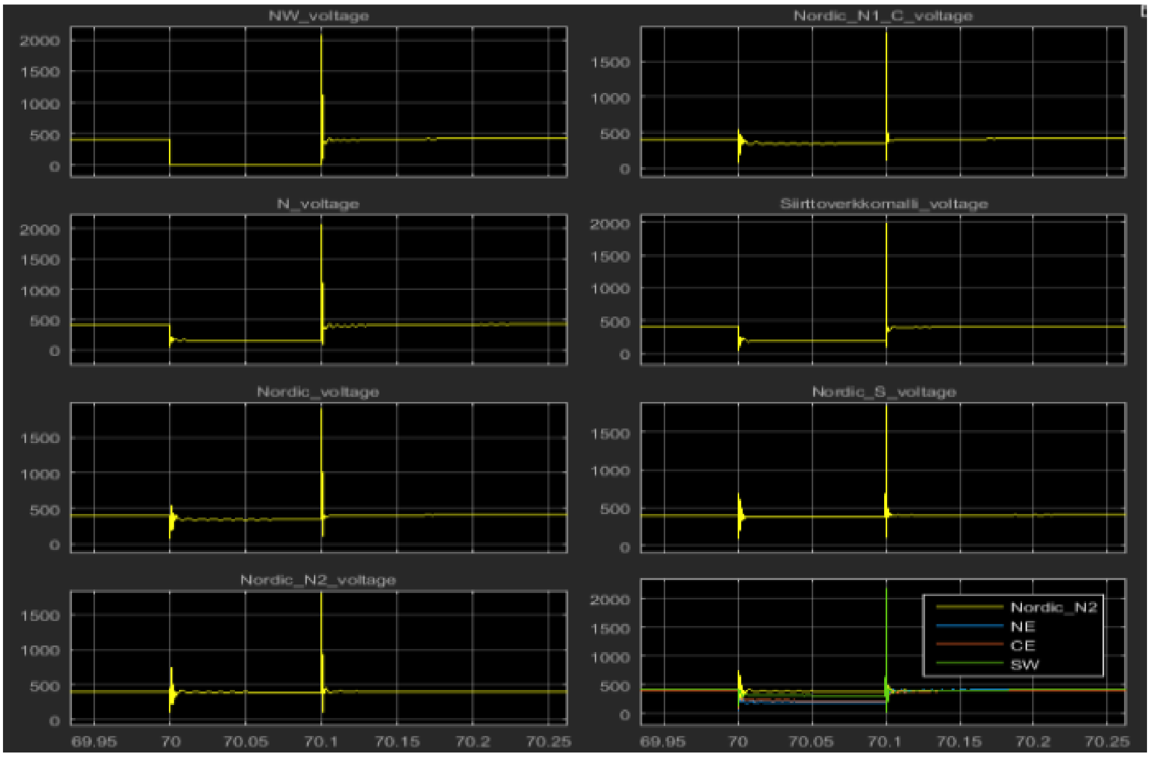

Figure 3.17(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault at NW bus

4. Case-4: 1100MW Export case (South-North), (Unstable case)

<u>When fault is at Paakaupunklseutu(S bus, 100ms) having loss of line between Rovaniemi(N) and Siirtoverkkomalli bus with increased electrical length by 100 %</u>

After a thorough study, it is deduced that in the case of 1100MW export from South to North, the system is unstable and the overall network performance seems disturbed. Large amount of active power has been exported from the southern side to the northern side identify points at which the system becomes unstable. Three-phase-to-ground fault having loss of line with increased electrical length have been applied as tests to study the system dynamic behavior. The plots for the generator frequency and bus voltages are shown in Figures 3.18(a), 3.18(b), 3.18(c), 3.18(d).

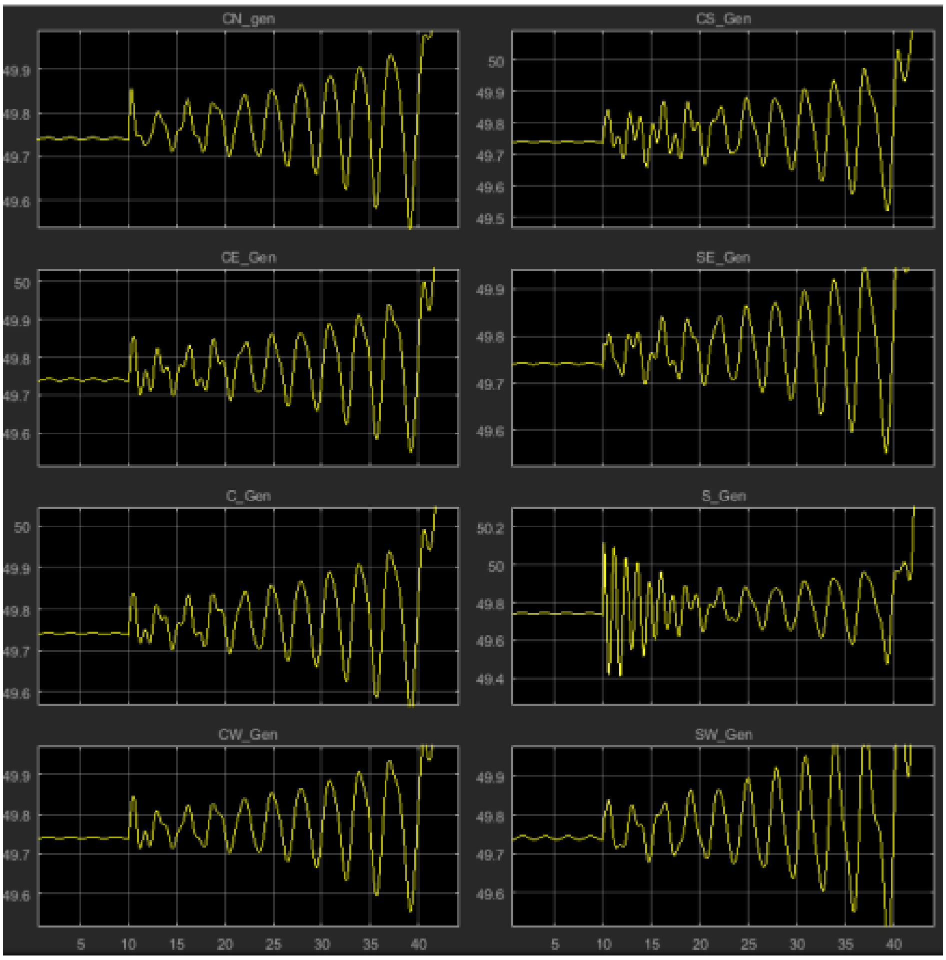

Figure 3.18(a): Frequency of Central and South generators under the under 3-phase-ground fault, 1100MW export case (Unstable case)

Figure 3.18(a),3.18(b) and 3.18(d) clearly depicts that the system becomes unstable after the application of fault at 10 seconds. After the occurrence of the fault, the system voltage and frequency starts oscillating at around 42 seconds of simulation time. Hence the system becomes unstable.

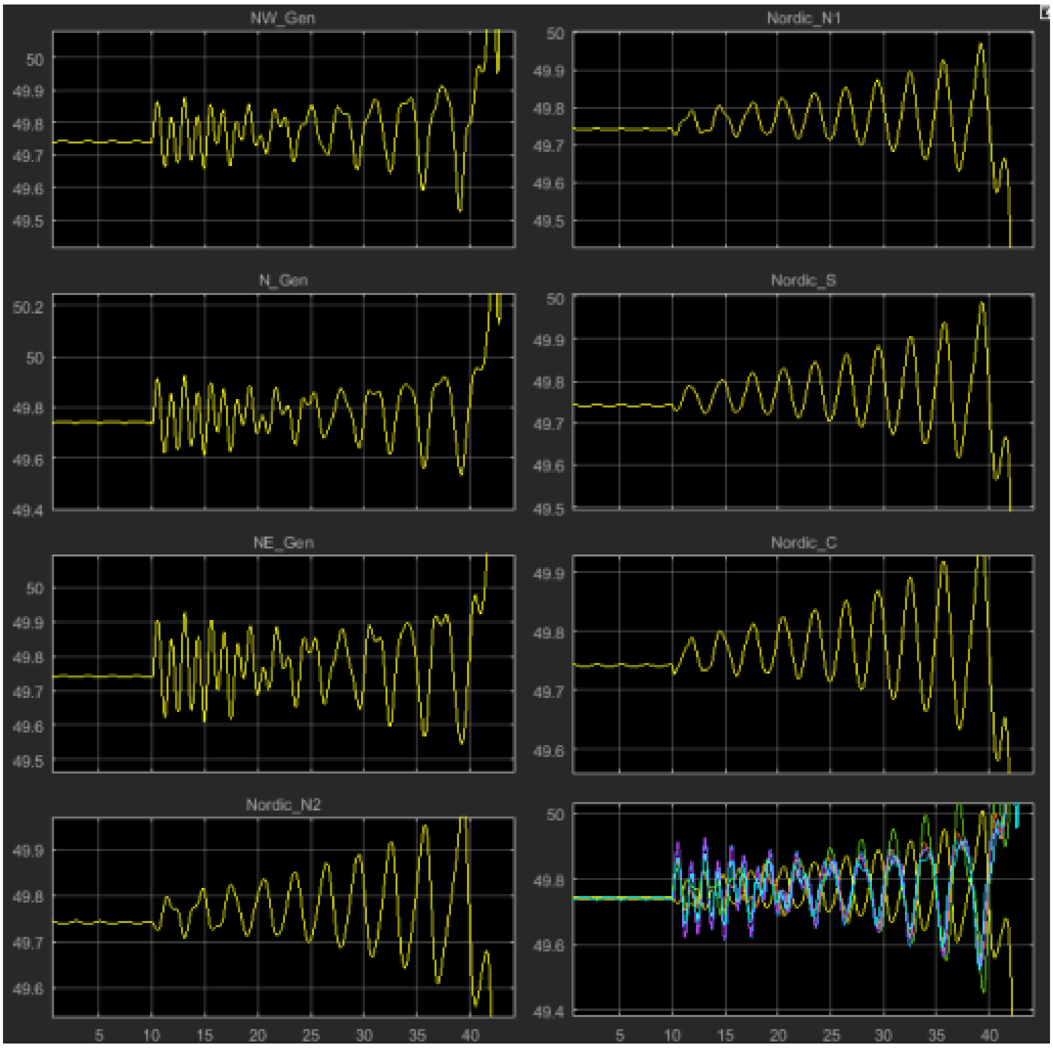

Figure 3.18(b): Frequency of North and Nordic generators under the under 3-phase-ground fault, 1100MW export case (Unstable case)

Lastly, it also observed that all the Nordic generators oscillate against the North, Central and South generators. Bus voltages lost its stability and the oscillations increased to a much greater extent.

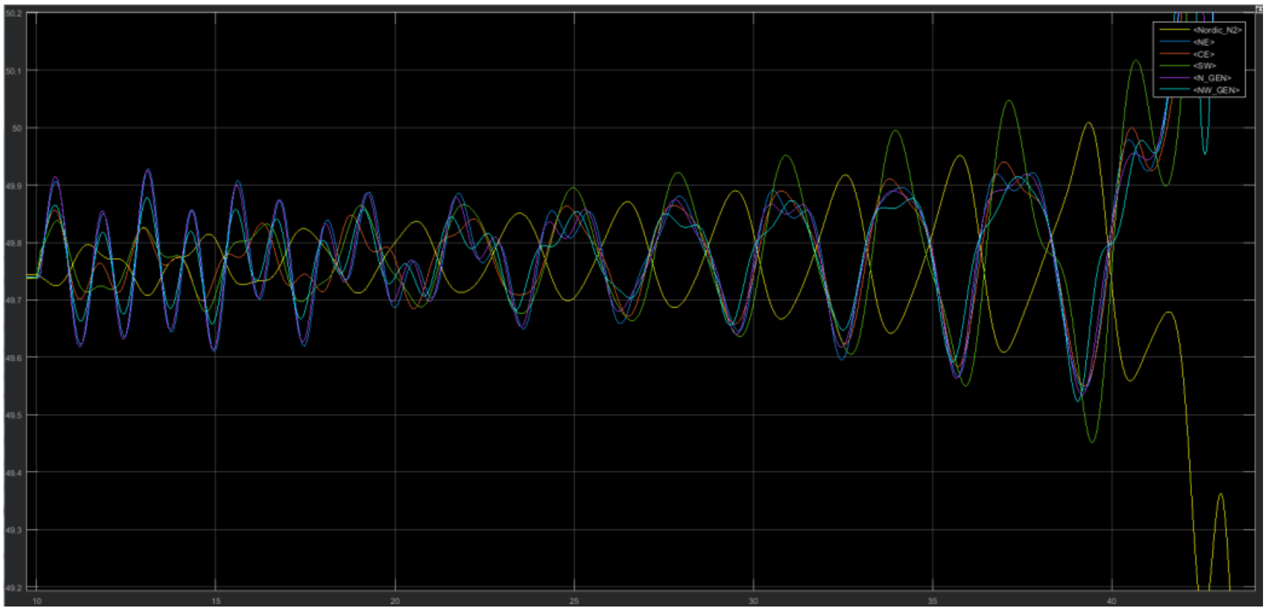

Figure 3.18(c): Frequency in several areas. (Nordic N2, NE, CE, SW, N, NW)

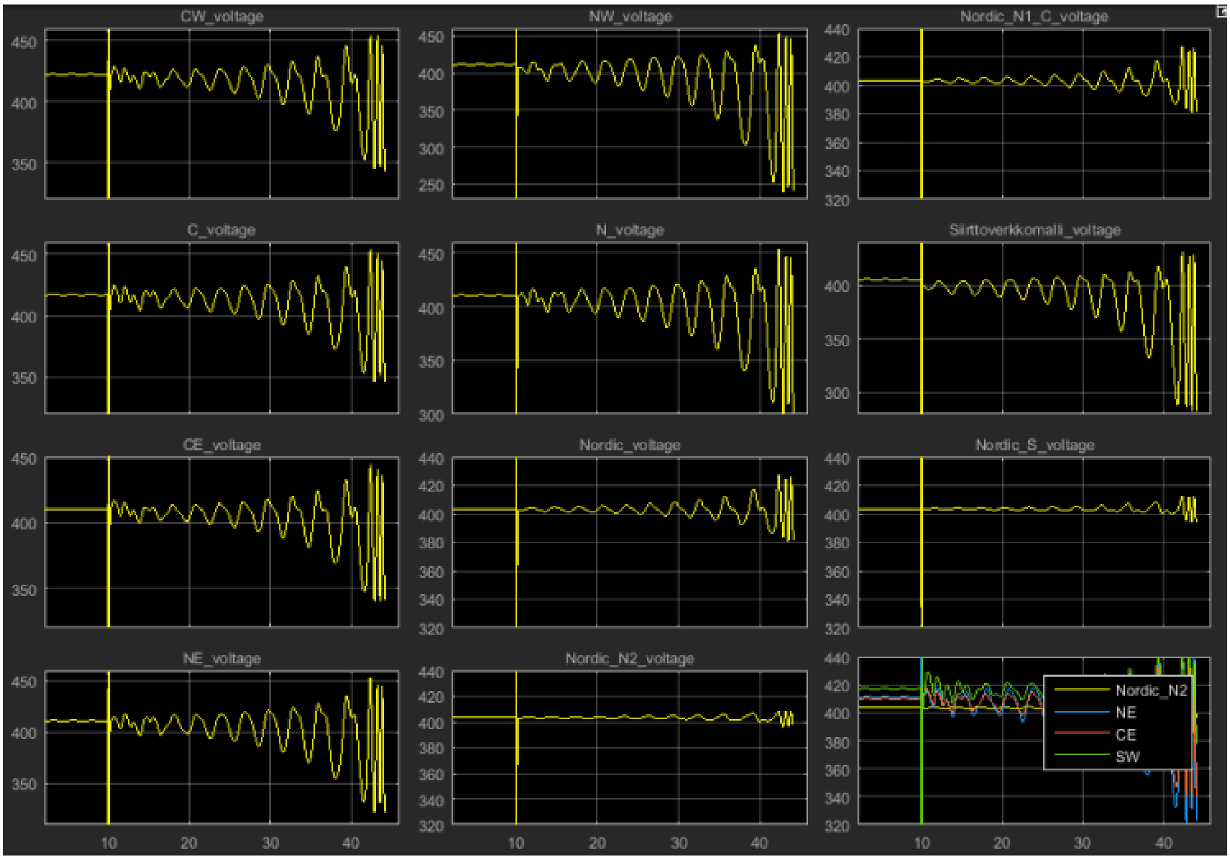

Figure 3.18(d): Voltage at 400kV buses under 3-phase-ground fault (unstable)

When fault is at Oulujoki(CN bus, 100ms) having loss of line between Kemijokisuu(NW) and Siirtoverkkomalli bus with increased electrical length by 100 %

In the following test case the fault location and loss of line was changed to different setting. The results obtained were analyzed and are presented by the Figures 3.20(a), 3.19(b), 3.19(c), 3.19(d).

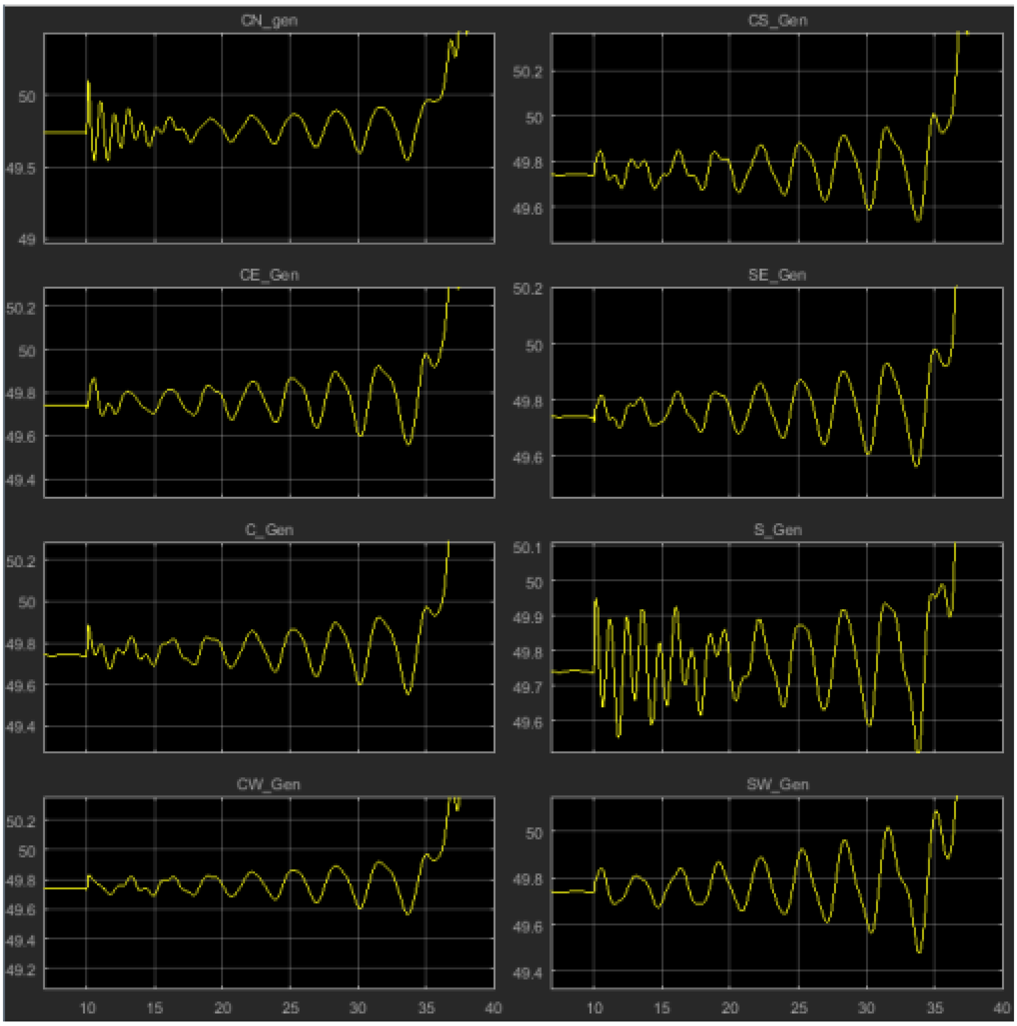

Figure 3.19(a): Frequency of Central and South generators under the under 3-phase-ground fault at CN bus, 1100MW (unstable case)

It can be seen from the Figure 3.19(a), 3.19(b), 3.19(d),3.19(e) that generator frequency becomes unstable after the fault occurrence and clearing the fault, oscillation becomes severe leading the bus voltages to collapse.

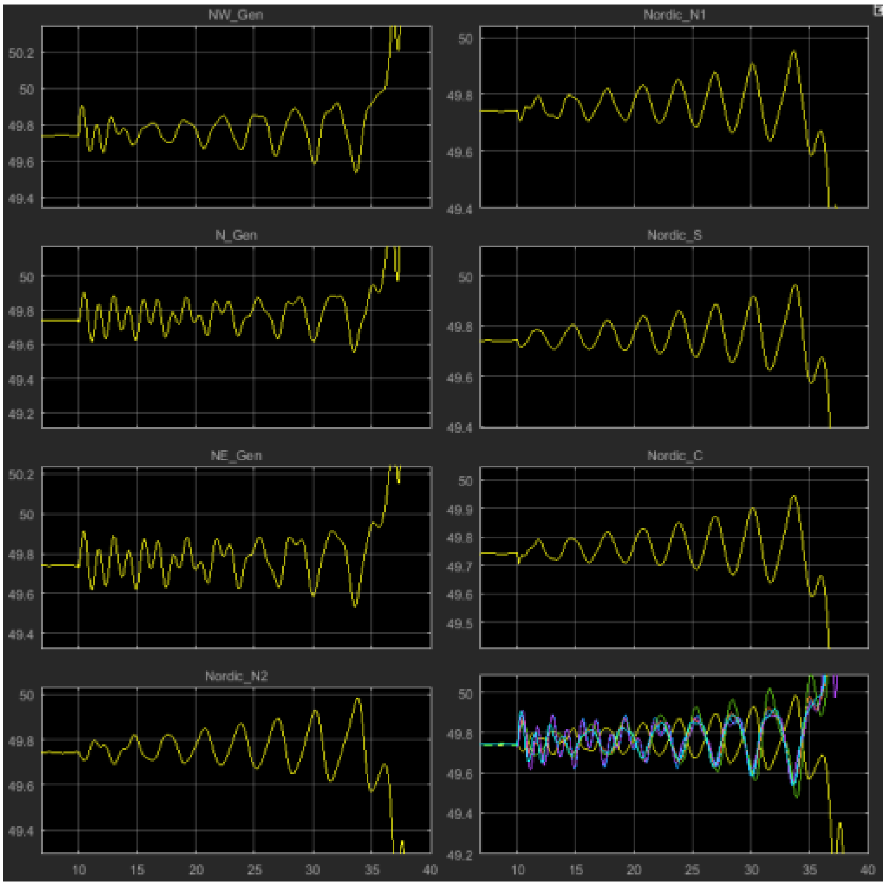

Figure 3.19(b): Frequency of North and Nordic generators under the under 3-phase-ground fault at CN bus, 1100MW (unstable case)

Figure 3.19(c) depicts that frequency in Nordic region spins against the frequency of North, Central and South region's generators.

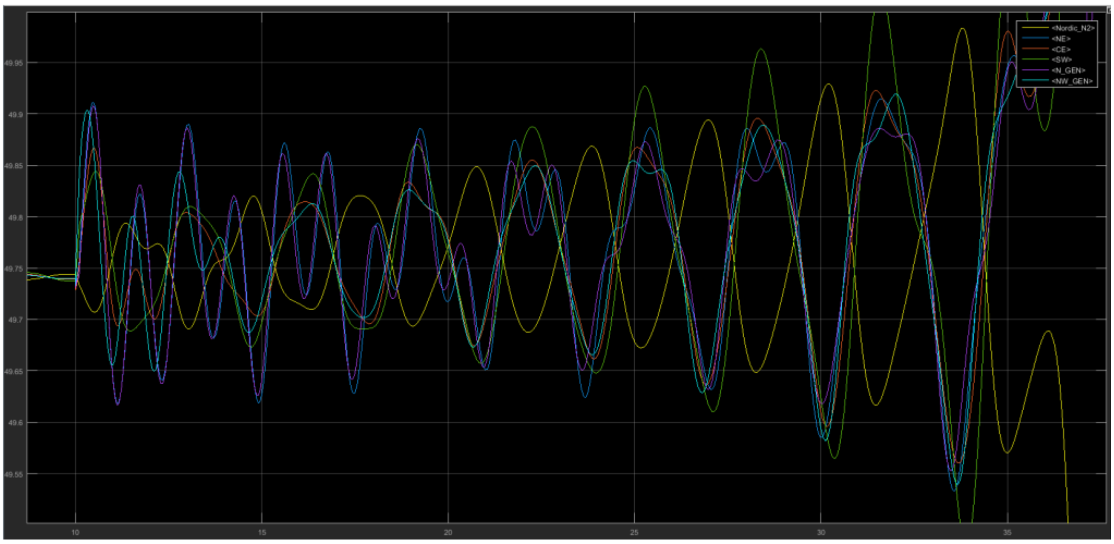

Figure 3.19(c): Frequency in several areas. (Nordic N2, NE, CE, SW, N, NW)

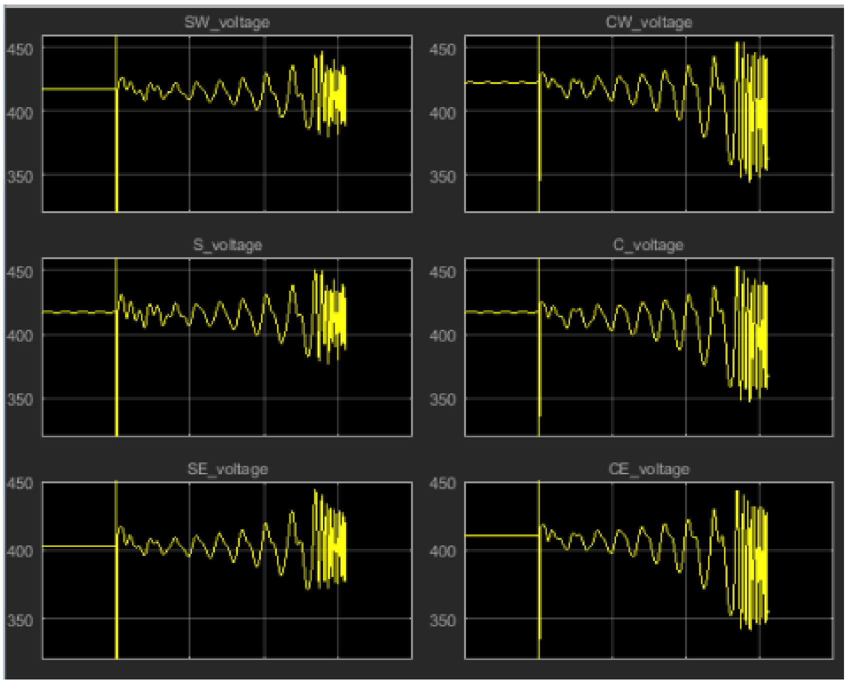

Figure 3.19(d): Voltage at 400kV buses South and Central region under 3-phase-ground fault (unstable)

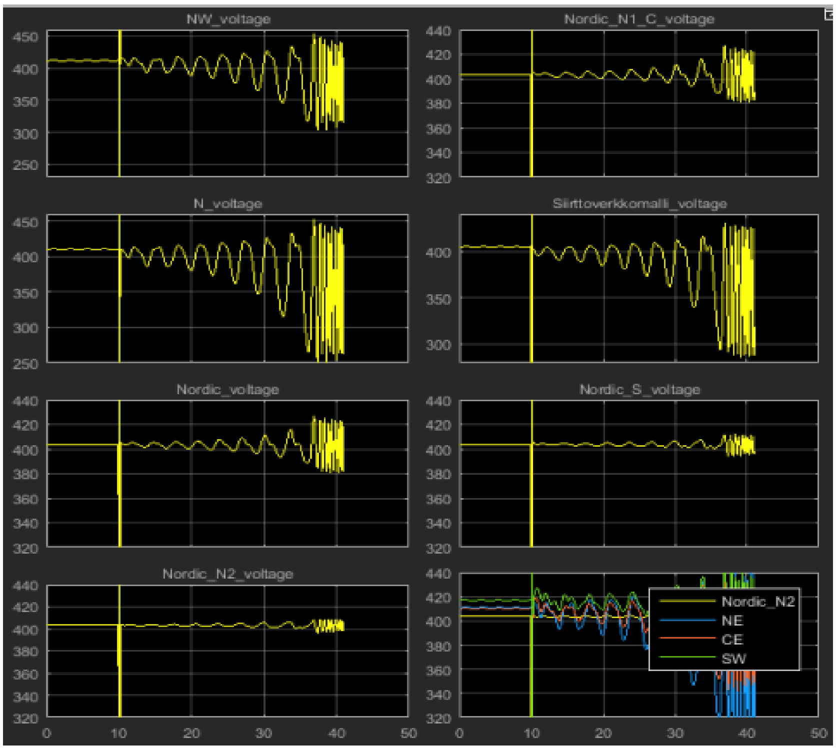

Figure 3.19(e): Voltage at 400kV buses North and Nordic region under 3-phase-ground fault (unstable)

5. Case-5: 1200MW Import case (Nordic-South), (Stable case)

<u>When fault is at Paakaupunklseutu(S bus, 60ms) having loss of line between Kemijokisuu (NW bus) and Siirtoverkkomalli bus with increased electrical length-100% increase</u>

The simulation results for the voltage and frequency curves are shown in Figures 3.20(a) and 3.20(b). The system becomes stable because of the fact that the governor circuits installed uplifts the frequency by increasing the mechanical power output even after the fault.

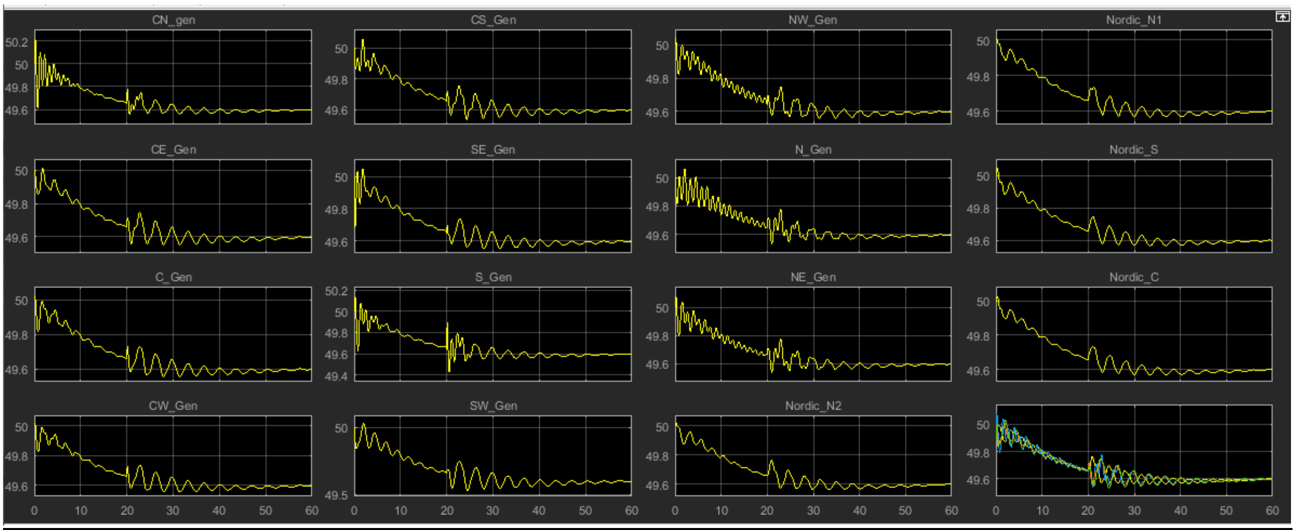

Figure 3.20(a): Frequency of generators under the under 3-phase-ground fault, 1200MW (Stable case)

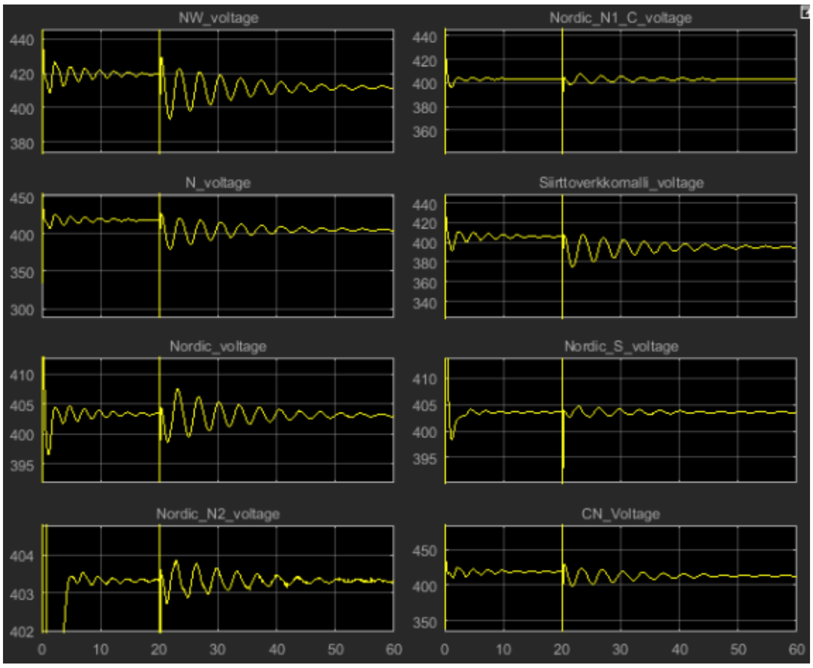

Figure 3.20(b): Voltage at 400kV buses North and Nordic region under 3-phase-ground fault (Stable case)

6. Case-6: 1400MW Import case (Nordic-South), (Unstable Case)

<u>When fault is at Paakaupunklseutu(S bus, 100ms) having loss of line between Kemijokisuu (NW bus) and Siirtoverkkomalli bus with increased electrical length-100% increase</u>

In this test case, the objective was to adjust the power flow such that to find out the highly unstable case.It is evident from the Figure 3.21(a) and 3.21(b) that the system loses its stability and the frequency becomes unstable after the fault. Regarding the oscillatory phenomenon, it is observed that all the Nordic generators oscillate against North, Central and South generators.

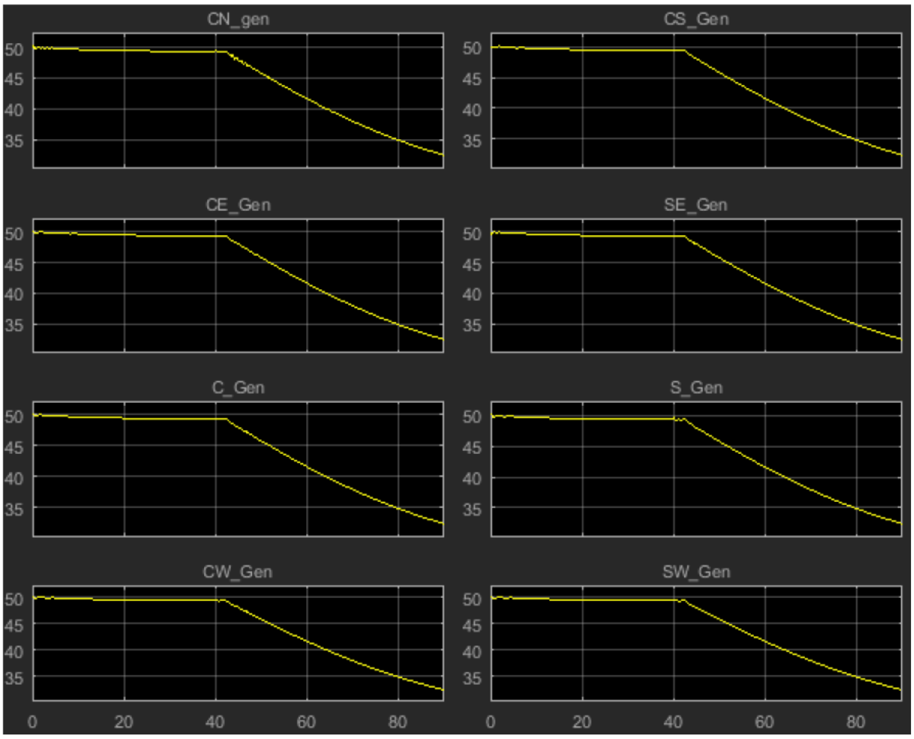

Figure 3.21(a): Frequency of Central and South region generators under the under 3-phase-ground fault, 1200MW (Highly Unstable case)

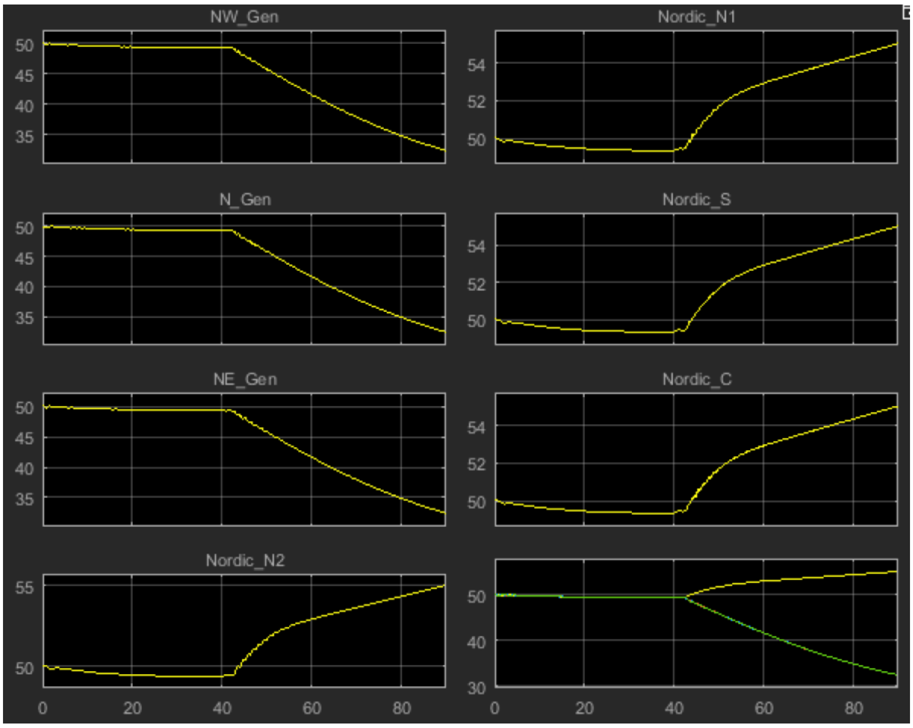

Figure 3.21(b): Frequency of North and Nordic region generators under the under 3-phase-ground fault, 1200MW (Highly Unstable case)

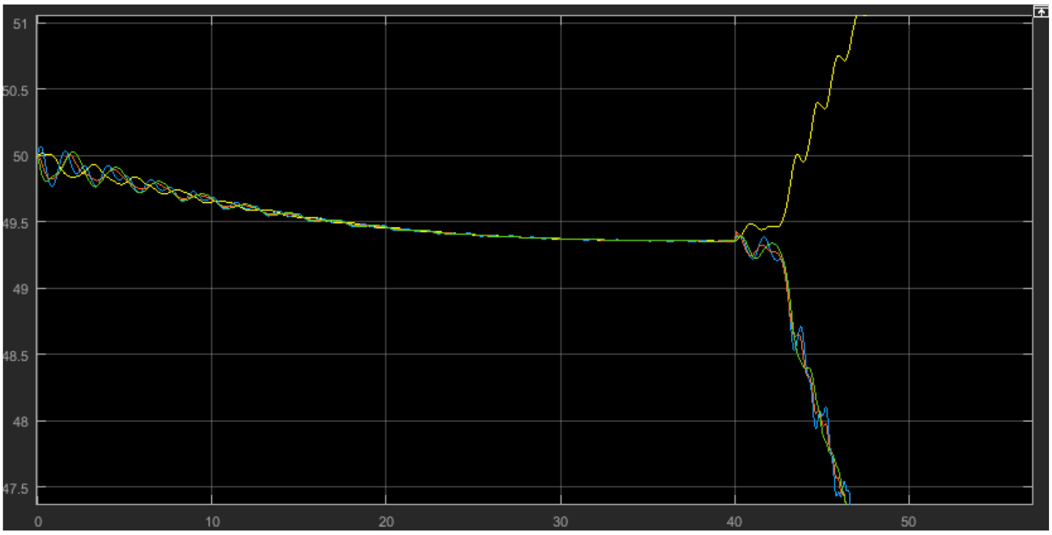

Figure 3.21(c): Frequency in several areas. (Nordic N2, NE, CE, SW, N, NW)

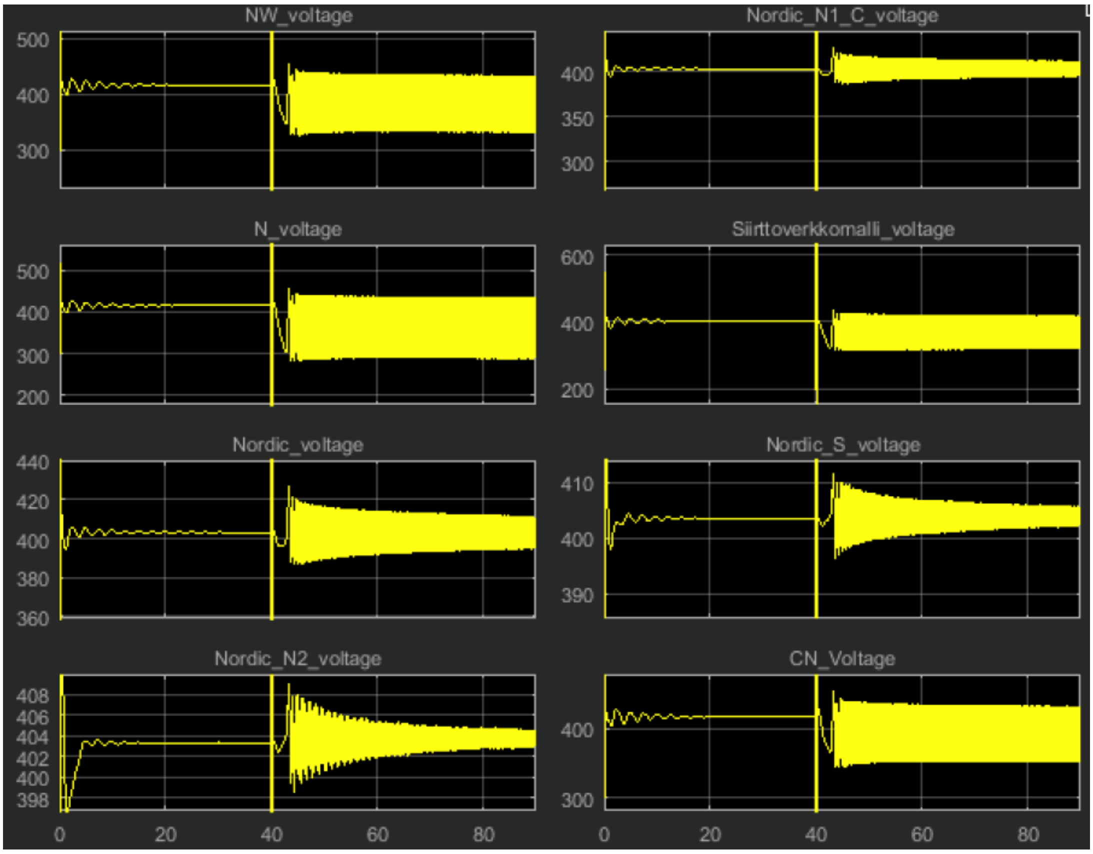

Figure 3.21(d): Voltage at 400kV North and Nordic region buses under 3-phase-ground fault (Unstable case)

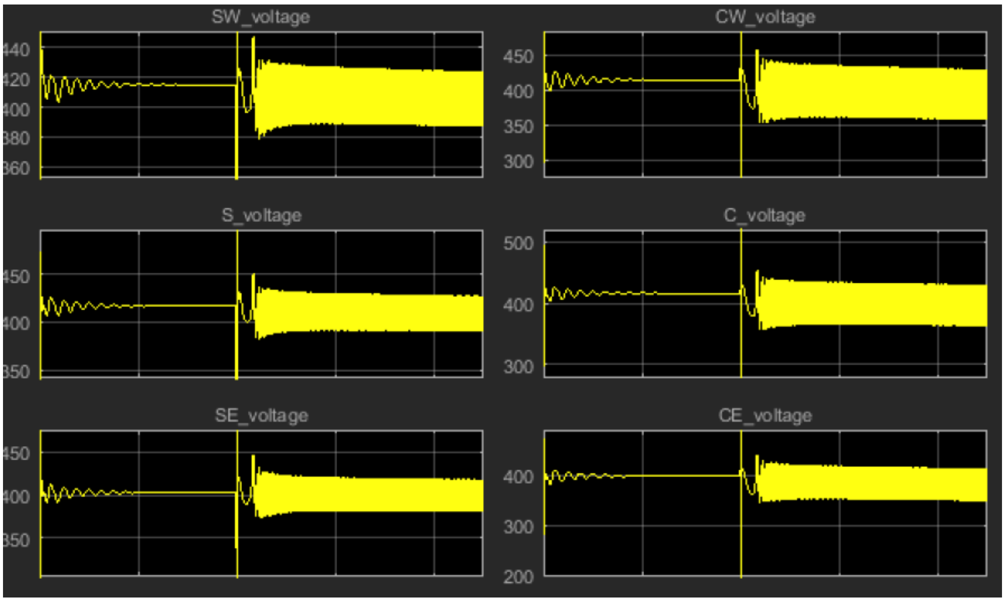

Figure 3.21(e): Voltage at 400kV South and Central region buses under 3-phase-ground fault (Unstable case)

The oscilatory phase depicted in the Figures 3.21(d) and 3.21(e) gives the information that the bus voltages lost its stability after the application of fault and as a result large scale oscillations resulted. Hence the overall network performance seems disturbed.

3.4 Summary and Discussion

It is observed that the model settles to a steady state operating point at the start although the initialization takes some time. The performance of the model was reviewed and it is observed that the model tolerates 400 kV 3pgh low-ohmic short circuit (no contingency) which is a good starting point. However, the damping of electromechanical oscillations is much better than in PSCAD model of the Fin Grid Siirtoverkkomalli. The results are depicted in the Figures 3.11(a),3.11(b),3.11(c),3.11(d). The scope of the simulations in Siirtoverkkomalli is to finalize the dynamic analysis of the system. In addition to this, the task was to analyze the stability limits of the system when power is transmitted from Nordic to South and South to North by testing few N-1 faults. Various test cases were conducted in order to have a deeper understanding of the network behavior. The power flow was adjusted to find out the two unstable cases i.e. highly unstable case and slightly unstable case.

4. N32 System and its Dynamic Equivalent

In this chapter, the system discussed and analyzed is the benchmark network model and a conceptualization of the Swedish transmission network in early 1990s. Then the implementation approach is reviewed and discussed. Later, reduction of the of the N32 model by using dynamic equivalents is presented. Lastly the equivalent model is connected to Siirtoverkkomalli and stability of the overall system is observed.

4.1 System Overview and Characteristics

The second test system implemented in this thesis is the Nordic 32 system. The model is basically a benchmark network model for voltage and transient stability analysis and reflects mainly the characteristics of Swedish transmission network in early 1990s. Generally, the topology of the N32 system is longitudinal, comprising of two large regions that are loosely connected through weak tie lines. The upper part of the system has North and Equivalent areas while the second region is formed by the Central and the South areas located in the bottom part [71]. The Nordic 32 system comprises of four various geographical territories, each having peculiar production and consumption features [72]

– 'North' with high levels of Hydro generation and low level of consumption
– 'Central' with Thermal generation and high level of consumption
– 'Southwest' with rather low Thermal generation and some load
– 'External' with moderate hydro production and moderate consumption

The transmission system consists of the main transmission network at 400kV (19 nodes) and two regional systems which operate at 130kV (11 nodes) and 220kV (2 nodes). The generation of the system is modeled with 23 generators i.e. 10 round rotor synchronous generators for the Thermal power plants, 12 salient pole synchronous generators for the Hydro power plants and 1 salient pole synchronous compensator. The main characteristic of the system is the long distances between the production center (North) and consumption center (Central). The high electrical distance between these areas has been reduced by the usage of series capacitance compensation in the 400kV transmission network.

An outline of the 400kV transmission network is illustrated in Figure 4.1 whereas the single line diagram of the Nordic 32 system is shown in Figure 4.2.

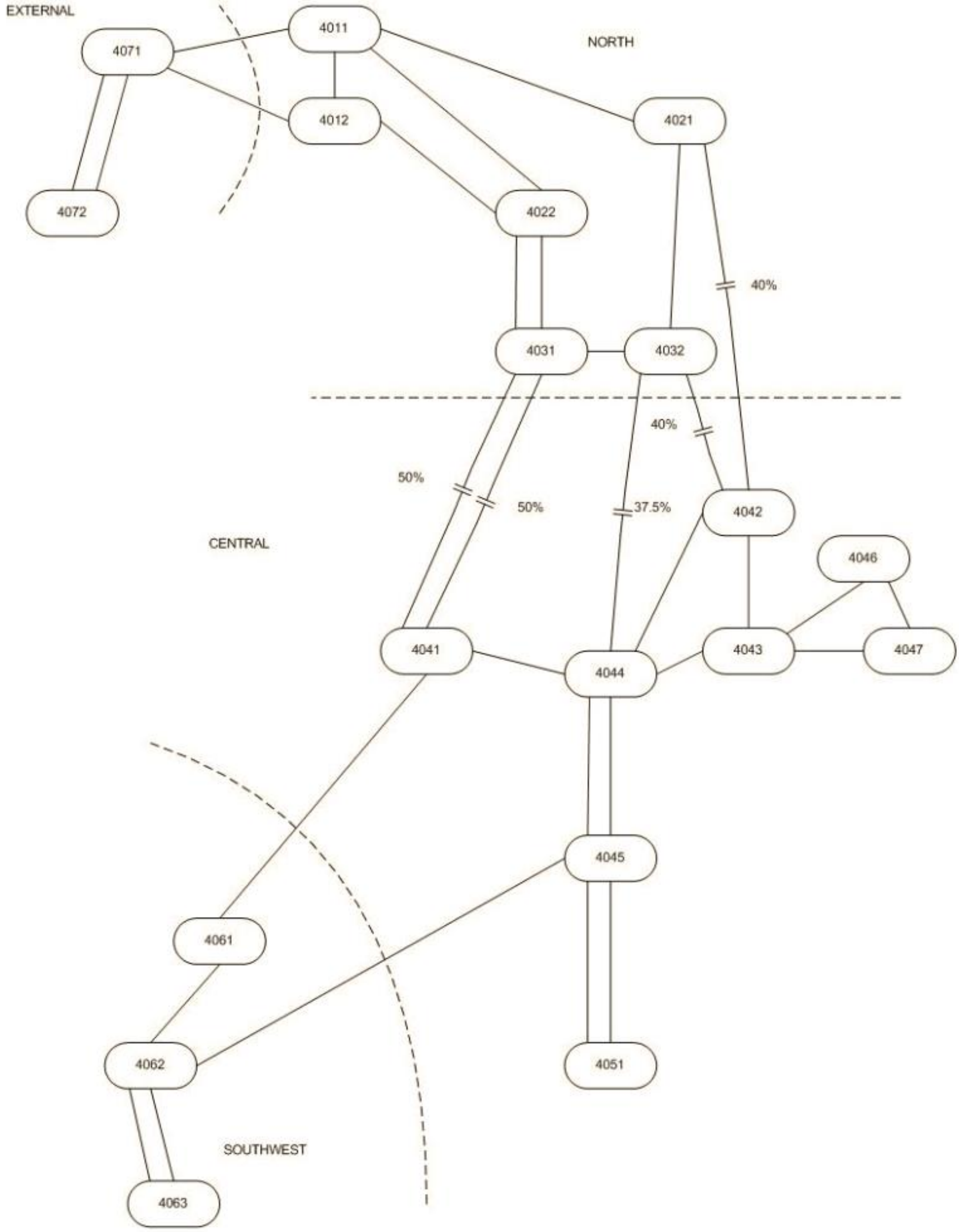

Figure 4.1: Graphical Outline of the 400kV transmission network of N32 [70]

4.2 Development and Implementation of the model

The development and implementation approach of Nordic 32 system is similar to that of the Siirtoverkkomalli. The power system modelling principles have been discussed in detail earlier in section 3.2.1.1 therefore they are not going to be discussed here in this chapter By applying the same techniques and principles of dynamic modelling of power systems, a MATLAB/Simulink based model of N32 system is successfully implemented. Only the 400kV transmission network is modelled initially. Originally the Nordic 32 system is implemented in PSAT. The system description provided in [70] is considered as a reference for the modelling purpose of the N32 system. The description can be seen in Appendix B.

4.2.1 Model and Data

1. **Buses**: The system has 52 node buses, 20 of which are generator buses. There are four level of voltages; 15 kV for generator buses, 20kV for distribution buses, 130kV, 220 kV and 400 kV for transmission buses [70].

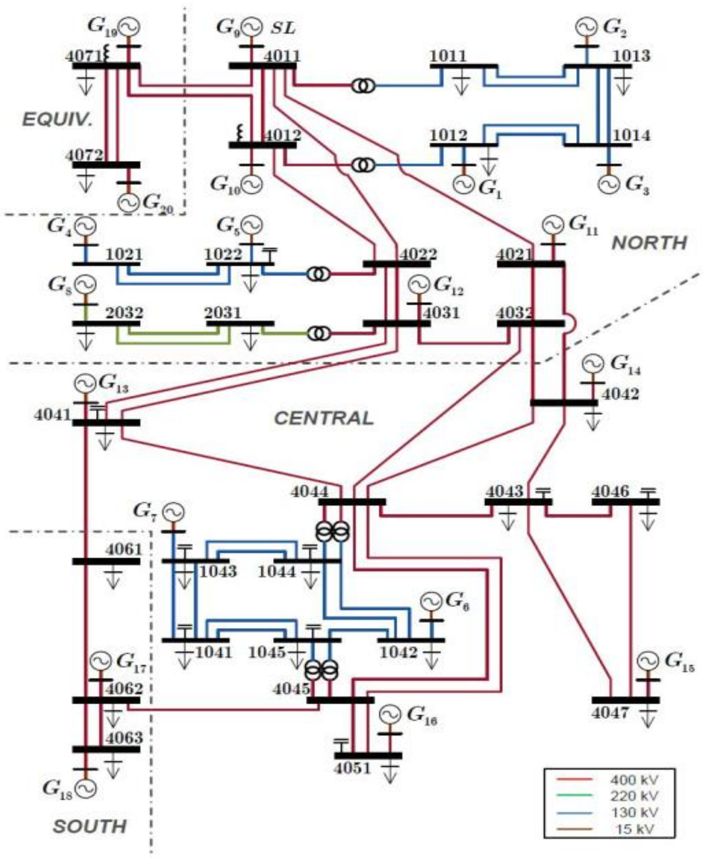

Figure 4.2: Nordic 32 system [70]

2. **PI-section models:** In MATLAB/Simulink the transmission lines are modelled using the block available as "three phase PI-section block" as shown in Figure 4.3. N32 is modelled with a total number of 29 transmission lines.

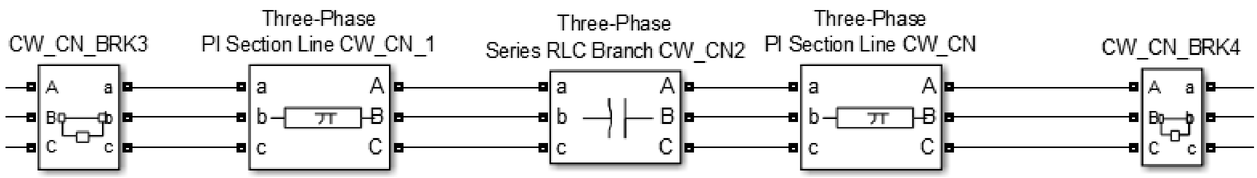

Figure 4.3: Configuration of transmission line in MATLAB/Simulink

3. **Constant Load models:** N32 comprises of the constant impedance load. The loads in N32 are modelled using constant impedance "Z" type. In the initialization of the model, the solver of the software does the transformation into constant impedances R_l and X_l (Eq. 3.1).

4. **Synchronous Generators:** Modelling of the synchronous generators is accomplished by two different synchronous generator models. Round rotor machines for nuclear and steam power plants (Order VI) modelled in the dq reference frame while salient pole synchronous machines for hydro power plants (Order V) also modelled in the dq reference frame. All the data follows Van Cutsem's proposed data [70] [72]. Generators and associated parameters are attached in Appendix- B.

5. **Shunt Elements**: The description of the shunt elements are as follows, 11 shunts, out of which 2 are inductor shunts (negative susceptance) while the rest are capacitor shunts (positive susceptance).

6. **Turbine Governors:** For the mechanical torque operation, two different categories of turbine governors are utilized in the network i.e. TG Type I (thermal generators) while TG Type II (hydro generators). The data for the two TGs is presented in [72]. The TG Type II model is depicted in Figure 4.4, and the TG Type I model is described in [72].

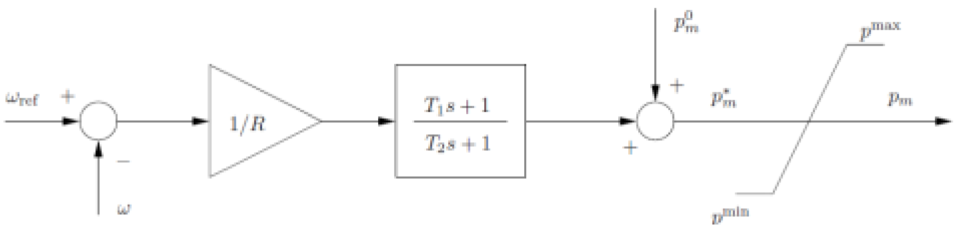

Figure 4.4: TG Type II model [73]

7. **Automatic voltage regulators(AVR):** All the generators in the N32 system are equipped with AVRs. The primary function of these regulators is to control and maintain the field voltage v_f. Figure 4.5 represents the AVR Type III model employed in the system [73] [74].

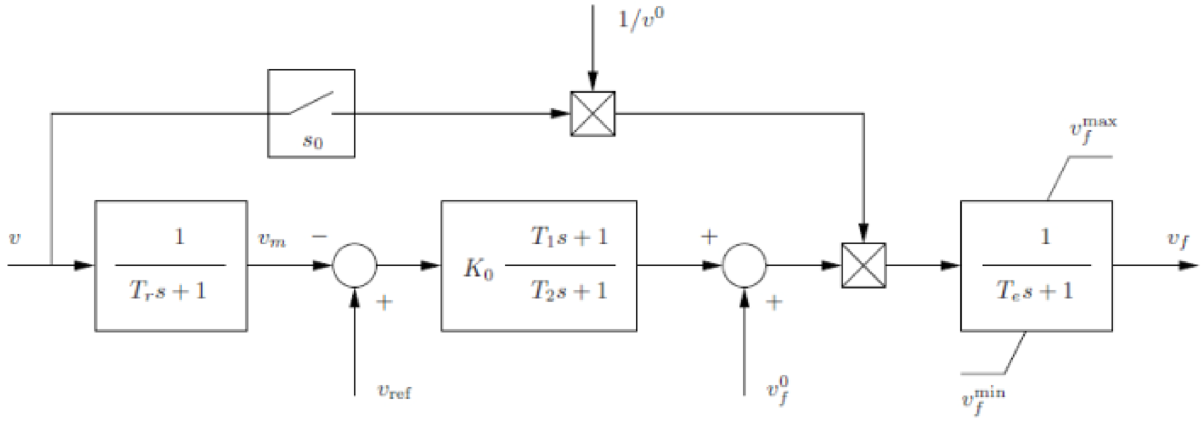

Figure 4.5: AVR Type III model [73]

8. **Over Excitation Limiters (OEL):** In order to keep the generator's field current within permissible range, the N32 system was equipped with over excitation limiters(OEL). As seen in Figure 4.6, the OEL is modelled as a pure integrator with anti-windup hard limits [73].

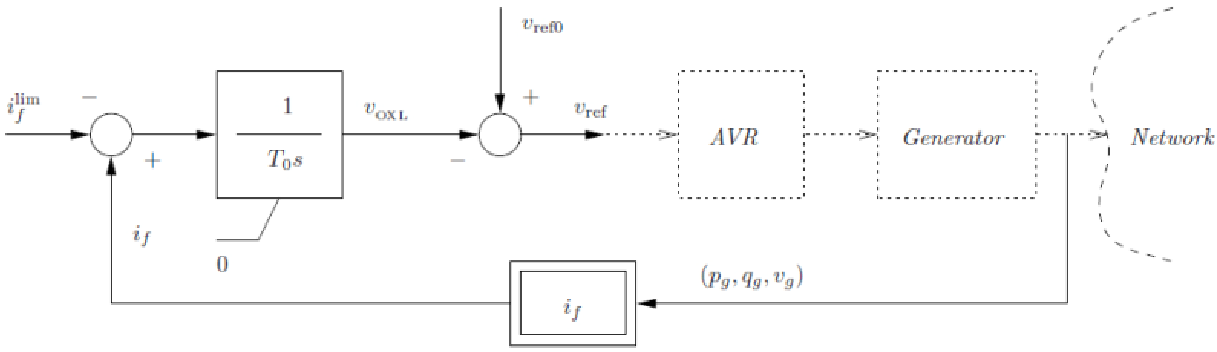

Figure 4.6: OEL model [73]

4.2.2 Zero Flow test case

In order to check the stability of the N32 system, a zero power flow test case is conducted. The frequency is tuned such that the generation and load is in balance and almost no power flows in the network. The test is initiated by applying a three-phase-to-ground fault in the North region. The prime objective of the zero power flow test conducted here is to check the stability and overall network performance of the N32 system in the presence of a network disturbance i.e. three-phase-to-ground fault. The ensuing frequency and voltage graphs are shown in Figures 4.7 and 4.8.

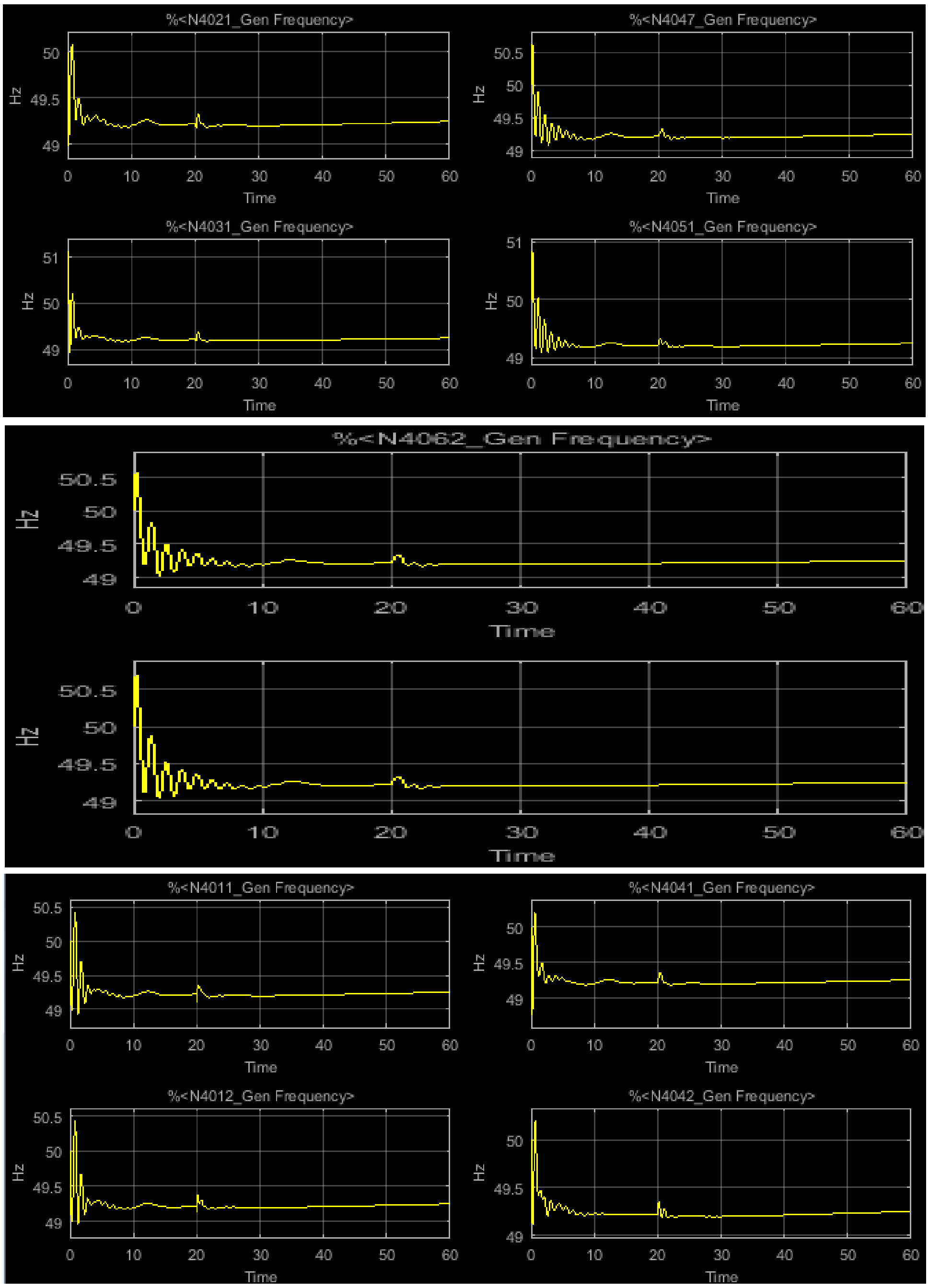

Figure 4.7: All generator frequencies of N32 system

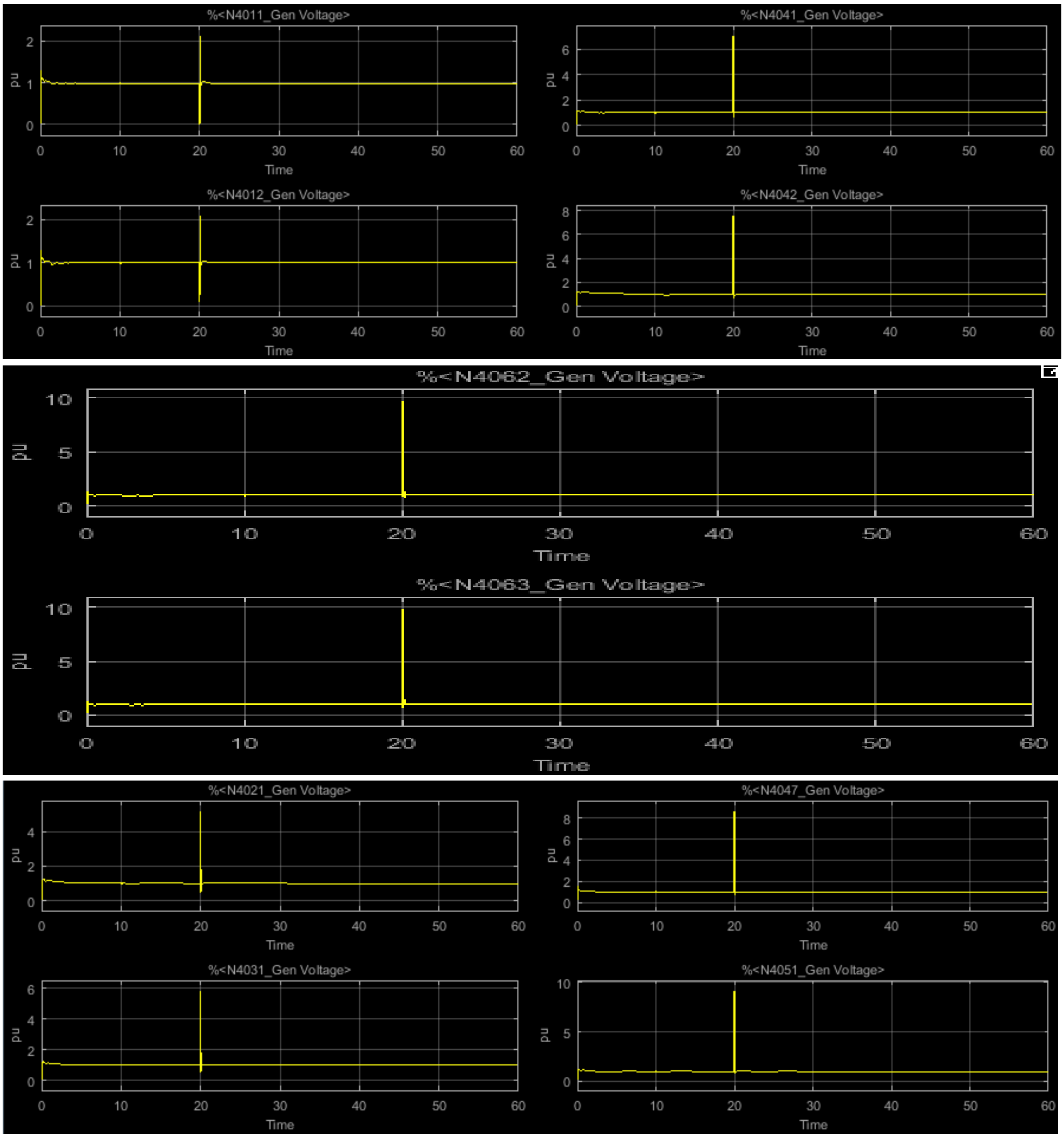

Figure 4.8: All node voltages of N32 system

It can be seen from the above plots that the overall network performance seems rather good. Even after the application of fault at 20ms the system stabilizes and all the bus voltages does not loses its stability.

4.3 Development of Dynamic Equivalent model of N32

This section elucidates the reduction of a power system by the dynamic equivalents approach. The goal is to construct a dynamic equivalent of N32 system and connect it to the Siirtoverkkomalli for dynamic analysis and as well as frequency and voltage support studies. Further elaboration is done in the next section.

4.3.1 Steps for the development of Dynamic Equivalent model of N32

The development part of the equivalent model of N32 have been accomplished by taking into consideration the following important steps.

- A proposal on DEs is studied and an approach to obtain DE is implemented
- Identification of coherent generator groups in N32
- Construction of N32 Dynamic Equivalent model

4.3.1.1 Approach adapted for building DEs

In this section, an approach adapted for constructing Dynamic Equivalent model of power system network is elaborated. In this regard, a method given in P.M. Anderson’s book on “Power System Control and Stability” is used to get a reduced dynamic equivalent of N32 system [75]. The method applied is very efficient and effective that yields accurate results for further transient stability studies. The method is implemented after the accomplishment of the following steps.

a) Extraction of nodal admittance and impedance matrix of N32 system.
b) Node elimination by using Kron’s reduction.

a) Extraction of nodal admittance and impedance matrix of N32 system

This is the first step in developing of the Dynamic Equivalent model. The practicality of admittance matrix is to analyze power networks for network power flow studies, frequency correction in electric networks and system reconfiguration for loss reduction in distribution systems. A MATLAB based program is coded for the impedance calculation and power flow analysis of N32 system. Initially, the program comprised of the separate functional blocks for each step of the impedance matrix method. These functional blocks included the blocks for transmission line data, nodal data (generation and load data), calculating the mismatch equations, forming the admittance matrix and lastly inverting it to get the impedance matrix.

In the first step of the implementation, all the separate functional blocks are combined together into a single MATLAB file for better understanding and to study the step by step functioning of the code. In this step all the base values are converted into per unit system for the sake of simplicity. Normally in classical power system transient analysis, the nodal admittance matrix of the overall network is transformed into an equivalent admittance system matrix where the objective is to retain all the generator buses and eliminating all the other nodes by mathematical computation [75]. As in the case of N32 system, the modelling is done only for 400kV lines and all the 17 nodes comprising the network are reduced to 9 nodes in the process of impedance calculation. The nodes having the generation are retained while all the other nodes are eliminated mathematically. The MATLAB code for the step by step calculation of nodal admittance matrix of the N32 system is shown by the Figures 4.9(a), 4.9(b), and 4.9(c).

```
%   bustype:    1.- Slack, 2.- PV, 3.- PQ,
%   Pg,Qg:      Active and reactive power of each generator.
%   Pd,Qd:      Demanded active and reactive power.
%   Bsh:        Capacitor or reactor connected to bus k.
%   MVAb = 100:        MVA base power .
%   Zb = 1600 Ohm
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                            % Power System Data (N32)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% N32_Nodal_Data
% Generator and load data

%                     Node  bustype     Pg         Qg         Pd          Qd          Bshc
data_gen_load_base = [1       1         2.088       -2.94      -1.839     -0.7995     0
                      2       2         2.748      -0.915     -2.688      -0.9993     0
                      3       2         0.8478     -3.52      -0.8089     -0.3998     0
                      4       3         0.0        0.0        0.0         0.0         0
                      5       2         0.8392     -3.937     -0.8444     -0.2998     0
                      6       3         0.0        0.0        0.0         0.0         0
                      7       2         -0.0562    -4.78      0.0000      0.0000      0
                      8       2         3.235      -4.528     -3.185      -1.256      0
                      9       3         0.0        0.0        0.0         0.0         0
                      10      3         0.0        0.0        0.0         0.0         0
                      11      3         0.0        0.0        0.0         0.0         0
                      12      3         0.0        0.0        0.0         0.0         0
                      13      2         0.798      -1.789     -0.8306     -0.4517     0
                      14      2         5.544      -1.32      -5.629      -2.531      0
                      15      3         0.0        0.0        0.0         0.0         0
                      16      2         2.472      -1.277     -2.486      -0.7996     0
                      17      2         3.854      -0.1149    -3.921      -2.561      0
                     ];
```

Program 4.9(a): M-file of N32 nodal data

Program 4.9(a) depicts the generator and load data of N32 system. In order to obtain the above data, the Simulink model have been built and simulated. Finally, the data is converted to per unit system for better understanding and visualization of the results.

Whereas the transmission line data and initialization of the generator and load data is illustrated in Figure 4.9(b) as (Program 4.9b).

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                            % Transmission Line Data (N32)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% N32_Trans_Line_Data
%                          %  Network data
%             From        To       R(pu)      X(pu)      Gsh(pu)    Bsh(pu)      tap
data_network=[1           2        0.001      0.008      0.0000     0.2010        1.12
              1           3        0.006      0.06       0.0000     1.7995        1.12
              1           4        0.004      0.04       0.0000     1.2013        1.12
              2           4        0.004      0.035      0.0000     1.0505        1.12
              3           6        0.004      0.04       0.0000     1.2013        1
              3           8        0.01       0.06       0.0000     3.0000        1
              4           5        0.004      0.04       0.0000     1.2013        1.07

              4           5        0.004      0.04       0.0000     1.2013        1.07
              5           6        0.001      0.01       0.0000     0.3015        1.05
              5           7        0.006      0.04       0.0000     2.3976        1.05
              5           7        0.006      0.04       0.0000     2.3976        1.05
              6           8        0.01       0.04       0.0000     2.0000        1
              6          10        0.006      0.05       0.0000     2.3976        1
              7          10        0.003      0.03       0.0000     0.8997        1
              7          15        0.006      0.045      0.0000     1.3018        1

              8           9        0.002      0.015      0.0000     0.4976        1
              8          10        0.002      0.02       0.0000     0.5981        1
              9          10        0.001      0.01       0.0000     0.3015        1
              9          12        0.001      0.01       0.0000     0.3015        1
              9          13        0.002      0.02       0.0000     0.5981        1
             10          11        0.002      0.02       0.0000     0.5981        1
             10          11        0.002      0.02       0.0000     0.5981        1
             11          14        0.004      0.04       0.0000     1.2013        1
             11          14        0.004      0.04       0.0000     1.2013        1
             11          16        0.011      0.08       0.0000     2.3976        1
             12          13        0.001      0.015      0.0000     0.4976        1
             16          17        0.003      0.03       0.0000     0.8997        1
             16          17        0.003      0.03       0.0000     0.8997        1

             ];
%From -> To: Connectivity of transmission lines.
%R,X,Gsh,Bsh: Transmission line parameters.
%tap(primary): If no transformer or transformer with nominal tap -> tap=1,
%secondary tap assumed to be 1.
num_nodes = length(data_gen_load_base(:,1));

nx = data_network(:,1);  ny = data_network(:,2);
r = data_network(:,3);   x = data_network(:,4);
Gsh = data_network(:,5); Bsh = data_network(:,6);
tap = data_network(:,7);

bus_type = data_gen_load_base(:,2);
Pg = data_gen_load_base(:,3);        Qg = data_gen_load_base(:,4);
Pd = data_gen_load_base(:,5);        Qd = data_gen_load_base(:,6);
Bshc = data_gen_load_base(:,7);
num_lines = length(nx);                                                                          %
```

Program 4.9(b): M-file of N32 transmission line data, initialization and calling of the data

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                            % Calculating Admittance Matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Compute Ybus
Ybus = zeros(num_nodes,num_nodes);

for k = 1:num_lines
     y = (r(k) + 1i*x(k))^-1
     Ybus(nx(k),nx(k)) = Ybus(nx(k),nx(k)) + 0.5*(Gsh(k)+ 1i*Bsh(k)) + y;
     Ybus(ny(k),ny(k)) = Ybus(ny(k),ny(k)) + 0.5*(Gsh(k)+ 1i*Bsh(k)) + y*tap(k)^2;
     Ybus(nx(k),ny(k)) = Ybus(nx(k),ny(k)) - y*tap(k);
     Ybus(ny(k),nx(k)) = Ybus(ny(k),nx(k)) - y*tap(k);
end

for k = 1:num_nodes
    Ybus(k,k) = Ybus(k,k) + 1i*Bshc(k);
end
Ybus
```

Program 4.9(c): Admittance matrix calculation algorithm

b) Node elimination by using Kron's reduction

At this point of the impedance calculation method, the matrix obtained is of the order 17x17. Therefore, after certain mathematical computation, all the other nodes (other than the generator buses) are eliminated, using Kron's reduction. Kron's reduction is a node elimination method used in bus admittance and impedance modelling [75]. The significance of this reduction is that it can be useful in analyzing a large interconnected power system if the interest is only in the voltages at certain specific buses of prime interest. The method explained in [75] is used as a reference to eliminate the nodes of the N32 system, that is not of prime interest in the development of a Dynamic Equivalent model. The formula shown in equation 4.1 can be directly used to calculate the reduced bus admittance matrix by selecting Y_{pp} as the pivot point while diminishing bus p.

$$Y_{jk(\text{new})} = Y_{jk} - \frac{Y_{jp}Y_{pk}}{Y_{pp}} \tag{4.1}$$

where i and j can be given all integer (1…N), row p and column p are to be diminished. In order to differentiate the elements of new bus admittance of order (N-1) x (N-1) from the original Y_{bus} a subscript (new) is employed in the formula.

The MATLAB code by utilizing the method discussed in [75] [76] is written to reduce the order of the network admittance matrix from 17x17 to 9x9. Finally, the inversion of admittance matrix gives us the impedance matrix. The Kron's reduction method is explained in Figure 4.10 as (Program 4.10).

```
%%                              Krons Reduction
%                               ***************
%  Krons reduction is used in Bus admittance and impedance  reduction and...
%  zbus building algorithms.

% =====================Reference==================================
% [1] Power system Analysis-john j Grainger, Willian stevenson,jr
% ================================================================


%%  User input
% matsize = input('Enter the  matrix size     ');
% Ybus = zeros(matsize);
% display('Enter each element by row');   % enter each elements of a row first then so on...
% for k = 1:matsize
%     for k = 1:matsize
%         Ybus(k,k) = input('Enter element      ');
%     end
% end
% display(Ybus);

%% Kron's reduction method
nodesToEliminate = [15,12,11,10,9,7,6,4];
originalMatSize = size(Ybus,1);

for k=1:size(nodesToEliminate,2)
    p = nodesToEliminate(k);
    newmatsize = originalMatSize-k;
    Ybus_new = zeros(newmatsize,newmatsize);
    for i = 1:newmatsize
        for j = 1:newmatsize
            Ybus_new(i,j) = Ybus(i,j) - (Ybus(i,p)*Ybus(p,j)/Ybus(p,p));
        end
    end
%      Ybus = Ybus_new
    zbus = inv(Ybus_new)
    display(zbus);
    %nodesToEliminate = nodesToEliminate - 1;
    %display(Ybus_new);
end
```

Program 4.10: Kron's reduction method

4.3.1.2 Identification of coherent generators in N32

The next step in the implementation of N32 Dynamic Equivalent is the identification of coherent generator groups. In this step of the implementation, the impedance matrix of the order 9 x 9 is reduced to 4 x 4 by grouping of coherent generators. The identification of coherent generators is initiated by getting the rotor angle curves of all the individual generators in the network. The method applied here is discussed in detail in P.M. Anderson's book on "Power System Control and Stability" [76]. Coherent generator groups are identified by applying certain engineering knowledge. The coherency is determined by the fact that a specific group of generators have the potential to swing together based on the generators' swing curves, corresponding to a wide range of network disturbances, such as changes in generation/load patterns, transmission line outages and short-circuit faults. Based on these swing curves, the generators are said to be coherent generators and are regarded as potential candidates to be grouped together forming one equivalent machine.

After analyzing the generators' rotor angle curves, 4 coherent generator groups were identified for making up the reduced equivalent network suitable for carrying out classical power system stability studies. The grouping done is as follows; Group1 (N4011, N4012, N4021, N4031), Group2 (N4047, N4062), Group3 (N4042, N4051) and Group4 (N4063). The simulation results for the detail testing of coherent generator groups are illustrated in the upcoming section 4.4. On the other hand, the method applied to get the further reduced impedance matrix incorporating the impact of coherent generator groups is presented in Figure 4.11 as (Program 4.11) [75].

```
%%
groups = {[1 2 3 4];[6 8];[5 7];[9]};
generatorsToEliminate = [];
numGroups = size(groups,1);
zbus_new = zbus;

% Rows
for i=1:numGroups
    generators = groups{i};
    zbus_new(generators(1),:) = mean(zbus(generators(:),:));
end

% Cols
for i=1:numGroups
    generators = groups{i};
    zbus_new(:,generators(1)) = mean(zbus(:,generators(:)),2);

    % Append list of generators to eliminate
    generatorsToEliminate = [generatorsToEliminate generators(2:end)];

end

% Eliminate extraneous rows and cols
zbus_new(generatorsToEliminate(:),:) = [];
zbus_new(:,generatorsToEliminate(:)) = [];
```

Program 4.11: Grouping of coherent generator groups to get a 4x4 Z_{bus}

Therefore, the reduced impedance matrix of the order 4 x 4 for the equivalent model of N32 is resulted. The resultant Z_{bus} matrix is in per unit scale and depicted in Figure 4.12.

zbus_new

4x4 complex double

	1	2	3	4
1	0.0040 + 0.0311i	0.0010 + 0.0073i	0.0008 + 0.0079i	0.0003 + 0.0029i
2	0.0010 + 0.0073i	0.0019 + 0.0156i	0.0004 + 0.0040i	0.0002 + 0.0020i
3	0.0008 + 0.0079i	0.0004 + 0.0040i	0.0013 + 0.0109i	0.0004 + 0.0035i
4	0.0003 + 0.0029i	0.0002 + 0.0020i	0.0004 + 0.0035i	0.0005 + 0.0047i

Figure 4.12: Impedance matrix of N32 Dynamic Equivalent model

The above values of R_l and X_l are again converted to actual values by taking into account the Z_{base} value as described in the MATLAB code. The resultant impedance matrix is symmetric. Furthermore, these values are used as an equivalent thevenin reactance in the Dynamic Equivalent model.

4.3.1.3 Construction of N32 Dynamic Equivalent model

In this section the modelling and construction of the equivalent model is accomplished by utilizing MATLB/Simulink environment. The model is implemented using the same modelling principles of power system as those applied in case of Siirtoverkkomalli and Nordic 32 models. The Simulink based equivalent model of N32 and one-line diagram of the equivalent model connected to Finnish transmission network are depicted in Figures 4.13 and 4.14 respectively.

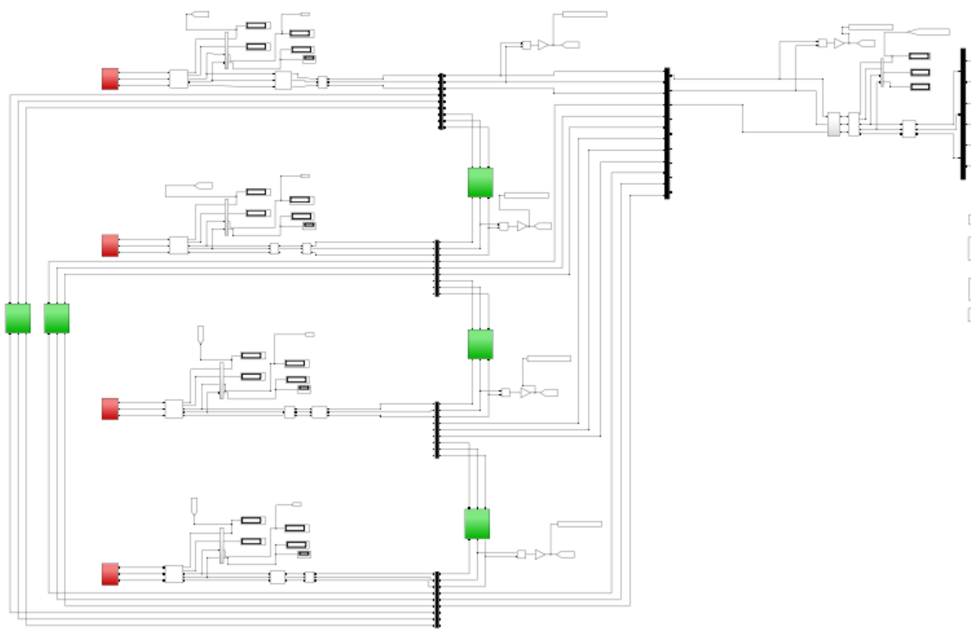

Figure 4.13: N32 Dynamic Equivalent model (Simulink based)

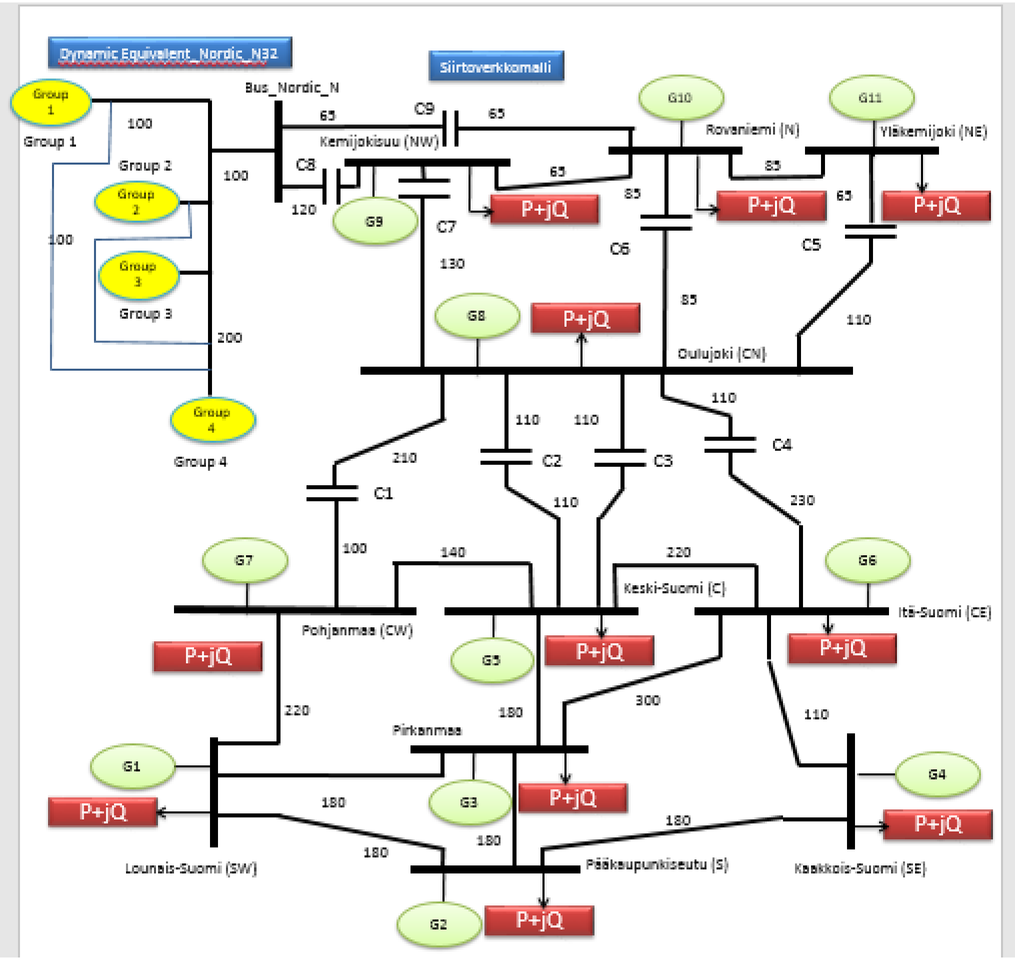

Figure 4.14: One- line diagram of N32 Dynamic Equivalent model connected to Siirtoverkkomalli

4.4 Simulation and Validation

In order to find out the robustness and efficiency of the developed equivalent model, few tests were performed. The groups of coherent generators in Nordic 32 have been determined based on the generators' swing curves, corresponding to a wide range of network disturbances, such as changes in generation/load patterns, transmission line outages and short-circuit faults. The results are summarized below and are illustrated by Figures 4.15 to 4.18.

Test 1: Changes in Gen/Load pattern (200MW), Fault in the North, With Loss of line from (N4061 to N4062)

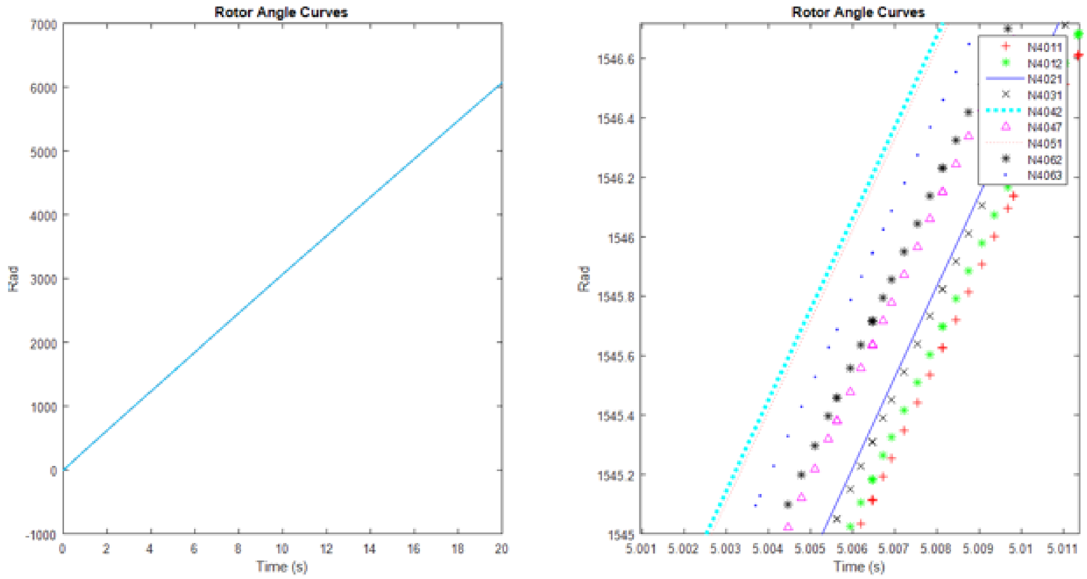

Figure 4.15: Rotor angle curves of N32 generators (Fault in the North)

Test 2: Changes in Gen/Load pattern (200MW), Fault in the South, With Loss of line from (N4011 to N4012)

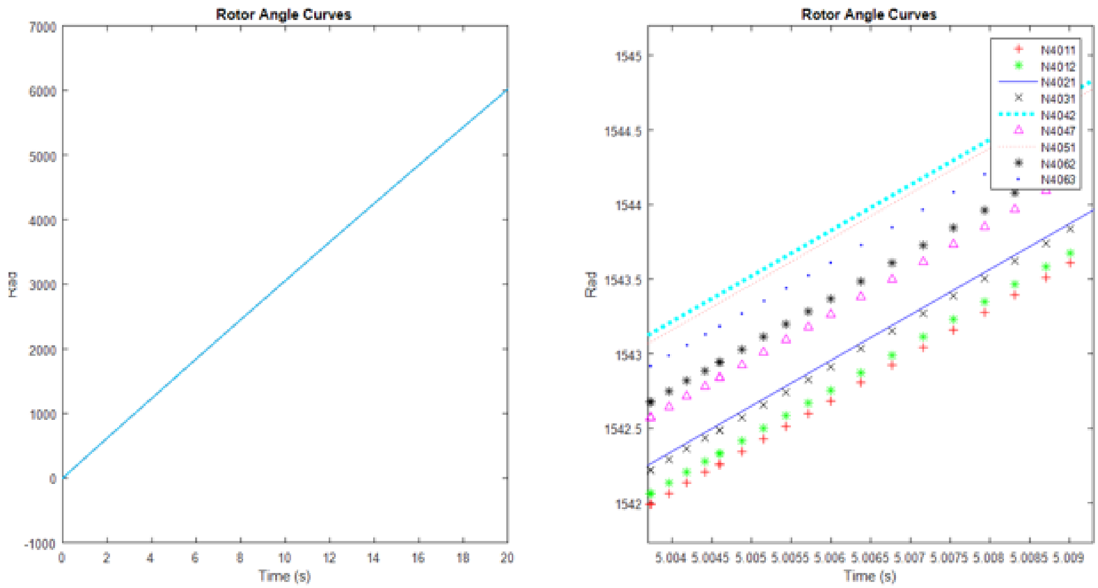

Figure 4.16: Rotor angle curves of N32 generators (Fault in the South)

Test 3: Changes in Gen/Load pattern 400MW, Fault in the North, With Loss of line from (N4061 to N4062)

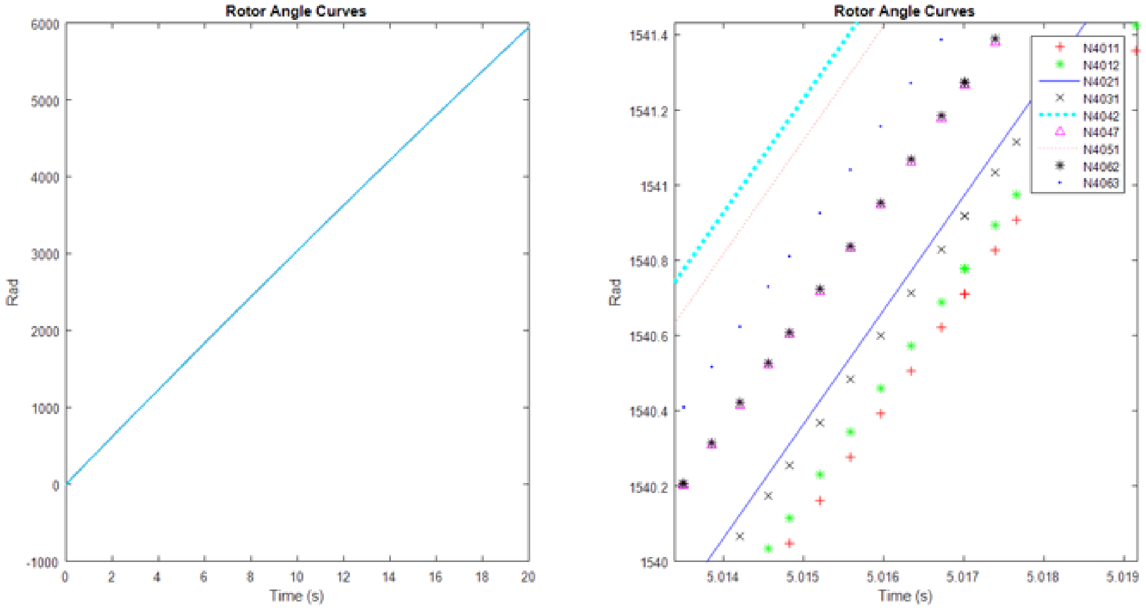

Figure 4.17: Rotor angle curves of N32 generators (400MW case)

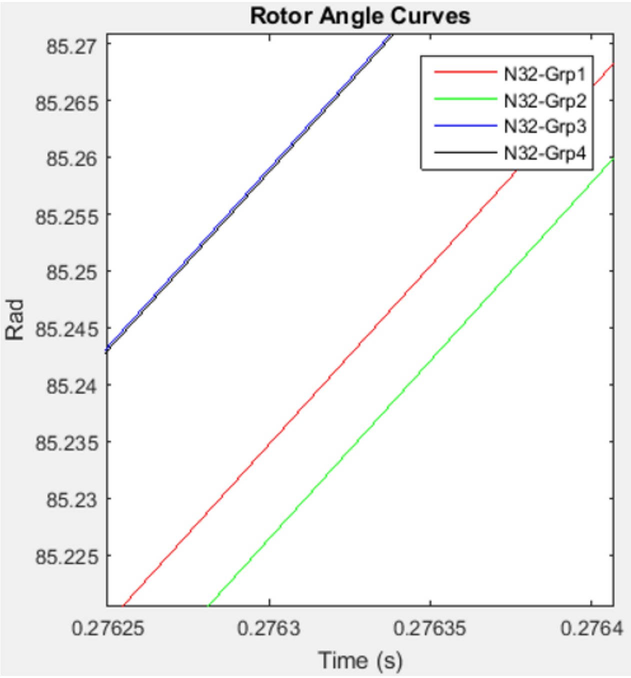

Figure 4.18: Rotor angle curves of the Dynamic Equivalent

Table 1. *Test Cases for Coherency Identification*

Network Disturbance Case	Where	Duration	ΔP	Transmission Line outages, Loss of line	CoherentGenerator Groups
Changes in Gen/Load Pattern, 3pgh fault	N	20 ms	+200 MW	From N4061 to N4062	G1(1,2,3,4),G2(6,8),G3(5,7) G4(9)
Changes in Gen/Load Pattern, 3pgh fault	S	20 ms	+200 MW	From N4011 to N4012	G1(1,2,3,4),G2(6,8),G3(5,7) G4(9)
Changes in Gen/Load Pattern, 3pgh fault	N	20 ms	+400 MW	From N4061 to N4062	G1(1,2,3,4),G2(6,8),G3(5,7) G4(9)

In all the three tests performed for the coherency identification, it is concluded that 4 coherent generator groups are identified for the development of the dynamic equivalent model of N32 system. Figure 4.15 to 4.17 shows a comparison of rotor angle variations of the coherent generators (in the full N32 system) along with their DEs (the reduced N32 system) for different fault location. It is depicted from the plots that the group's equivalent generator's rotor angle curves approximate those of the coherent generators. The coherent generator groups are presented and documented above in Table 1. During the coherency tests, for the sake of simplicity, following representation is used for the nodes name used in N32 system. **N4011 as node 1, N4012 as node 2, N4021 as node 3, N4031 as node 4, N4042 as node 5, N4047 as node 6, N4051 as node 7, N4062 as node 8, N4063 as node 9.**

Another set of simulations of the frequency curves of the N32 system and the equivalent model also depicts that system behavior of both the models are preserved. The summarized response of the two systems is depicted in Figure 4.19. After the comparison of the frequency curves of the equivalent system simulation and the original system simulation, it is concluded that the accuracy of the equivalent is very good. The coherency technique applied to obtain the DE is effective and successful. The transient stability swing curves are closely coherent. It is obvious that during the transient stability simulation, several units in the group oscillated with respect to the rest of the units which is due to the interaction of the controllers represented during the transient stability study. The four responses in Figure 4.19 illustrates that system behavior of the two systems is preserved. However, the only exception occurred in the fourth group which was large and remote from the fault. The fourth coherent group comprised of only one machine therefore the first thing that comes to mind is that it should have exactly the same response as that of the original system generator response. As it is an interconnected network therefore the responses of the equivalent system cannot be exactly same as of the original system solely because of the impact the equivalent machines have on each other.

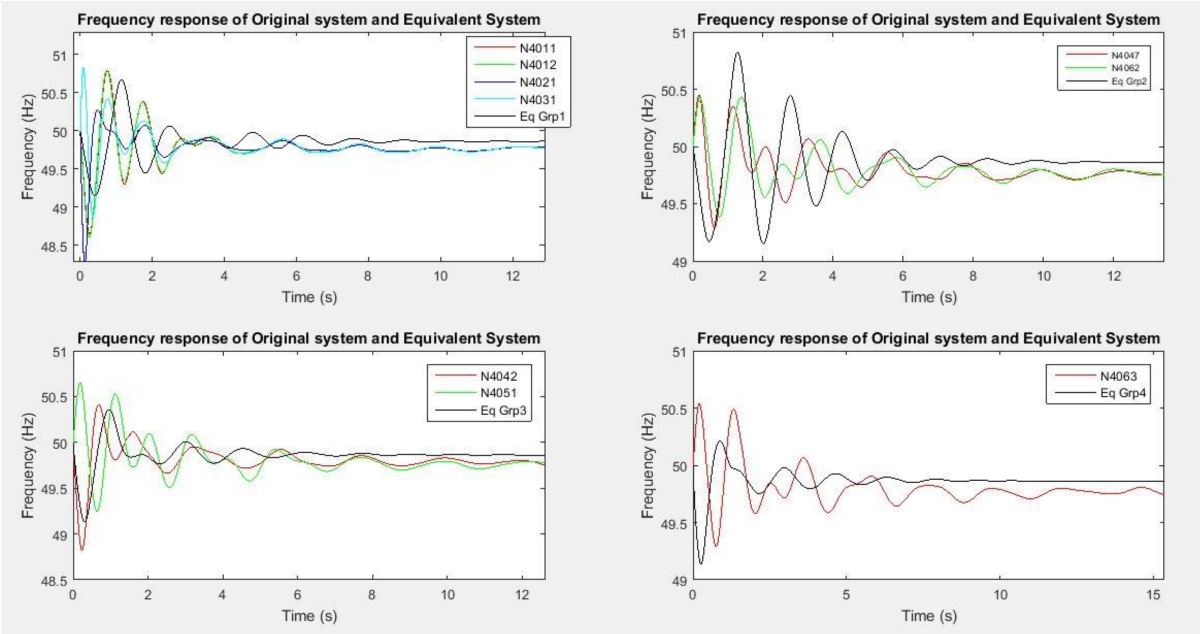

Figure 4.19: Frequency response of original system(N32) and equivalent system

Table 2. *Simulation speed comparison of equivalent Nordic32 with detailed Siirtoverkkomalli network*

Case	Elapsed time of the system with Equivalent model (90s simulation run time)	Elapsed time of the system without Equivalent model(90s simulation run time)
With 3pgh fault at single node	47 min	64 min
Without 3pgh fault at single node	8 min	15 min

In addition to the response of the four equivalent machine, the time taken for the simulations with and without equivalents was measured. The data is summarized and illustrated as in Table 2. It is justifiable after analyzing the above data that by utilizing the concept of equivalents we are actually saving time.

4.5 Summary and Discussion

In this section the objective was to develop a dynamic equivalent model that is capable of depicting the system behavior of the original system i.e. in this case is N32 system. The equivalent model established by coherency techniques proved to be successful and well working after a series of simulations. After obtaining dynamic equivalents, the number of generators in the system were reduced from 17 to 4. The simulations were performed for the zero power flow case, in which almost zero power flows throughout the bus. The local load demand has been met by the local generators. A three-phase-ground fault has been applied in the North region. The ensuing frequency behavior is shown in Figure 4.19. It can be seen from these results that the frequency behavior of the original system and the equivalent model is very close to each other. The frequency plots of both the models depicts that system behavior of both the models are preserved.

After a series of simulations performed for the N32 network and the DE model, it is therefore concluded that both systems gets stable to a pre-fault steady state. Therefore, the results obtained confirmed that the dynamic and transient characteristics of the N32 system (in this case it is the original system) are preserved by the dynamic equivalent model established. The overall network performance is really good and the system is stabilizes at 49.8 Hz at the end of simulation. Lastly the equivalent model is verified by connecting it to the Siirtoverkkomalli and simulated for stability check.

5. Conclusion and Future work proposal

The main focus of this thesis is to analyze the dynamic performance of different generic network equivalents using MATLAB/Simulink. In addition to this, the objective of this thesis is to implement and characterize the dynamic response of the Nordic 32 system using dynamic network equivalents. Secondly, the simulation studies in Siirtoverkkomalli and different power transfer capability analysis have been performed. This thesis work has presented an extensive review regarding the concept, theory and implementation of dynamic equivalents. It is worth mentioning here that there are two networks studied and implemented in this thesis for dynamic analysis: *Siirtoverkkomalli and Nordic 32*. The idea was to implement and model the two networks in MATLAB/Simulink environment so that they will be capable to contemplate various different facets of technical performance of transmission network such as transient stability, frequency variations and phenomena in series compensated network. In this regard, additional testing starting from basic load flow calculation have been performed.

After the implementation of the Siirtoverkkomalli (reflection of Finnish transmission network model) few load flow tests were performed in order to envisage the transmission capability assessment of the network. During the second phase of the thesis, another model i.e. Nordic 32 and its dynamic equivalent has been implemented by applying coherency techniques. The pertinent features of the modelling process, its elements and their configuration along with its operation and control has been described for a basic understanding.

In Siirtoverkkomalli further analysis and investigation was done by checking different power flow cases and analyzing the performance by fault and load drop simulations. The scope of the simulation was the analysis of transmission capability (stability limits of the mode) when power is transmitted from Nordic to South and vice versa. In other words, power flow was adjusted to find similarly slightly unstable case and highly unstable case. In the case of N32 system, the network was initially modelled and its dynamic equivalent was proposed and implemented in order to incorporate its impact on Siirtoverkkomalli to carry out voltage and frequency support studies.

Lastly it is concluded from the results that both the systems are stable and the overall network efficiency of the system seems quite reasonable, corresponding to wide range of network disturbances such as, changes in generation and load patterns, three phase-to-ground fault and transmission line outages. It is also evident from the results that the dynamic and transient characteristics of the N32 system (in this case it is the original system) are preserved by the dynamic equivalent model established. Last but not the least, the dynamic equivalent model of N32 is connected with Siirtoverkkomalli to check the robustness and stability of both the system. Hence, the results from simulations verify that the two models implemented are stable.

Future work proposals

Due to the complexity of power systems, the power engineers have been facing difficulties in simulating and studying large scale interconnected power networks for a significant long time. Need of the hour is to seek new ways and research methods for power system stability studies in order to counter the high penetration of renewable energy resources into power networks. To do so, some suggestions for future work are listed as follows:

- Proposing new simplification techniques for large power systems
- Suitable equivalents for distribution systems needs to be established
- Regarding the Simulink environment, the initialization feature for the load flow calculation of the *powergui* block need to be studied and investigated. The convergence problem of large networks in MATLAB/Simulink environment must be researched.

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Appendix A. Siirtoverkkomalli System Description

A.1 All generator parameters

No of gen.	Generator rating (MVA)	X_d	X_d'	X_d''	X_q	X_q'	X_q''	Xl	T_{do}'	T_{do}''	T_{qo}'	T_{qo}''	H(s)	F
G1	3700	1.79	0.355	0.275	1.66	0.57	0.275	0.215	7.9	0.032	0.41	0.055	8	0.001
G2	1450	2.183	0.413	0.339	2.157	1.285	0.332	0.246	5.69	0.041	1.5	0.144	4	0.001
G3	1220	1.798	0.324	0.26	1.778	1.051	0.255	0.193	5.21	0.042	1.5	0.042	4	0.001
G4	2000	1.782	0.444	0.283	1.739	1.201	0.277	0.275	6.07	0.055	1.5	0.152	5.5	0.001
G5	1220	1.798	0.324	0.26	1.778	1.051	0.255	0.193	5.21	0.042	1.5	0.042	4	0.001
G6	1220	1.798	0.324	0.26	1.778	1.051	0.255	0.193	5.21	0.042	1.5	0.042	4	0.001
G7	1220	1.798	0.324	0.26	1.778	1.051	0.255	0.14	5.21	0.042	1.5	0.042	4	0.001
G8	970	0.93	0.302	0.245	0.69	-	0.27	0.244	8	0.03	-	0.06	4	0.001
G9	710	0.92	0.3	0.22	0.51	-	0.29	0.13	5.2	0.029	-	0.034	6	0.001
G10	710	0.92	0.3	0.22	0.51	-	0.29	0.13	5.2	0.029	-	0.034	6	0.001
G11	710	0.92	0.3	0.22	0.51	-	0.29	0.13	5.2	0.029	-	0.034	6	0.001
G12	5910	0.92	0.3	0.22	0.51	-	0.29	0.13	5.2	0.029	-	0.034	6	0.001
G13	5910	0.92	0.3	0.22	0.51	-	0.29	0.13	5.2	0.029	-	0.034	6	0.001
G14	5000	2.183	0.413	0.339	2.157	1.258	0.332	0.246	5.69	0.041	1.285	0.332	4	0.001
G15	5000	2.183	0.413	0.339	2.157	1.258	0.332	0.246	5.69	0.042	1.285	0.332	4	0.001

A.2 Load parameters

Load Reactive power (MVar)	Load Active power (MW)	Load Bus name
0	570	SW
0	570	S
0	570	SE
0	285	CS
0	428	C
0	285	CE
0	428	CW
0	570.858	CN
0	285.4296	NW
0	85.713	N
0	85.713	NE

A.3 Parameters of the step-up transformers (at the generator terminals)

Gen. Step up Transformer	Nominal Power (MVA)	Winding-1 voltage (kV)	Winding-2 voltage (kV)	Winding Resistance (pu)	Leakage inductance (pu)	Winding connections
T1	5550	26	400	0.003	9.5493e-4	Yg-Yg
T2	1500	26	400	0.003	9.5493e-4	Yg-Yg
T3	1850	26	400	0.003	9.5493e-4	Yg-Yg
T4	3000	26	400	0.003	9.5493e-4	Yg-Yg
T5	1850	26	400	0.003	9.5493e-4	Yg-Yg
T6	1850	26	400	0.003	9.5493e-4	Yg-Yg
T7	1850	26	400	0.003	9.5493e-4	Yg-Yg
T8	1500	26	400	0.003	9.5493e-4	Yg-Yg
T9	1100	26	400	0.003	9.5493e-4	Yg-Yg
T10	1100	26	400	0.003	9.5493e-4	Yg-Yg
T11	1100	26	400	0.003	9.5493e-4	Yg-Yg
T12	8800	26	400	0.002	6.3662e-4	Yg-Yg
T13	8800	26	400	0.002	6.3662e-4	Yg-Yg
T14	7500	26	400	0.002	6.3662e-4	Yg-Yg
T15	7500	26	400	0.002	6.3662e-4	Yg-Yg

A.4 Capacitance parameters

Capacitor no.	C1	C2	C3	C4	C5	C6	C7	C8	C9
Capacitance (μF)	44.45	62.63	62.63	40.53	78.74	81.06	106	106	106

A.5 Parameters of the step-down transformers (at the load terminals)

Gen. Step up Transformer	Nominal Power (MVA)	Winding-1 voltage (kV)	Winding-2 voltage (kV)	Winding-3 voltage (kV)	Shunt Reactor (H)	Winding-1 Resistance (pu)	Winding-1 Leakage inductance (pu)	Winding -2 Resistance (pu)	Winding-2 Leakage inductance (pu)	Winding-3 Resistance (pu)	Winding-3 Leakage inductance (pu)	Winding connections
TL1	3000	400	110	20	100	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL2	3000	400	110	20	0.01	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL3	1850	400	110	20	100	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL4	1500	400	110	20	100	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL5	2500	400	110	20	0.006	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL6	2500	400	110	20	0.008	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL7	1500	400	110	20	0.0035	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL8	3000	400	110	20	0.03	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL9	1500	400	110	20	0.03	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL10	1000	400	110	20	0.03	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1
TL11	1000	400	110	20	0.03	1.047e-3	3.3327e-4	2.095e-4	6.6686e-4	6.35e-4	2.0213e-4	Yg-Yg-D1

A.6 Transmission line parameters

Node From-To	Length of lines	Number of lines	Positive sequence resistance (Ω/km)	Positive sequence inductance (H/km)	Positive sequence Capacitance (F/km)	Zero sequence resistance (Ω/km)	Zero sequence inductance (H/km)	Zero sequence Capacitance (F/km)
SW-S			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
SW-CW			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
SW-CS			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
S-SE			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
S-CS			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CW-C			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
C-CE			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
C-CS			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
SE-CE			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CS-CE			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CW-CN			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
C-CN			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CE-CN			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CN-NW			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CN-N			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
CN-NE			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
NE-N			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
N-NW			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
N-Nordic_N			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
NW-Nordic_N			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
Nordic_N-Nordic			2.282e-2	6.6362e-4	1.2775e-8	0.0684	3.3e-3	1.991e-3
Nordic-Nordic-N1			2.282e-2	1.1e-3	1.2775e-8	0.0684	3.3e-3	3.83e-8
Nordic-Nordic-S			2.282e-2	6.6362e-4	1.2775e-8	0.0684	3.3e-3	1.991e-3

Appendix B. N32 System Description

B.1 Busbars

Node	Nominal Voltage (kV)	Type	Active Load (MW)	Reactive Load (MVar)	Shunt Impedances		Area
					Active Compensation (MW)	Reactive* Compensation (MVar)	
4071	400	PV	300	100	0	-400	External
4071	400	PV	2000	500	0	0	External
4011	400	Slack	0	0	0	0	North
4012	400	PV	0	0	0	-100	North
4021	400	PV	0	0	0	0	North
4022	400	PQ	0	0	0	0	North
4031	400	PV	0	0	0	0	North
4032	400	PQ	0	0	0	0	North
1011	130	PQ	200	80	0	0	North
1012	130	PV	300	100	0	0	North
1013	130	PV	100	40	0	0	North
1014	130	PV	0	0	0	0	North
1021	130	PV	0	0	0	0	North
1022	130	PV	280	95	0	50	North
2031	220	PQ	100	30	0	0	North
2032	220	PV	200	50	0	0	North
4041	400	PV	0	0	0	200	Central
4042	400	PV	0	0	0	0	Central
4043	400	PQ	0	0	0	200	Central
4044	400	PQ	0	0	0	0	Central
4045	400	PQ	0	0	0	0	Central
4046	400	PQ	0	0	0	100	Central
4047	400	PV	0	0	0	0	Central
4051	400	PV	0	0	0	100	Central
1041	130	PQ	600	200	0	200	Central
1042	130	PV	300	80	0	0	Central
1043	130	PV	230	100	0	150	Central
1044	130	PQ	800	300	0	200	Central
1045	130	PQ	700	250	0	200	Central
41	130	PQ	540	128.3	0	0	Central
42	130	PQ	400	125.7	0	0	Central
43	130	PQ	900	238.8	0	0	Central
46	130	PQ	700	193.7	0	0	Central
47	130	PQ	100	45.2	0	0	Central
51	130	PQ	800	253.2	0	0	Central
4061	400	PQ	0	0	0	0	Southwest
4062	400	PV	0	0	0	0	Southwest
4063	400	PV	0	0	0	0	Southwest
61	130	PQ	500	112.3	0	0	Southwest
62	130	PQ	300	80	0	0	Southwest
63	130	PQ	590	256.2	0	0	Southwest

* The sign (+) corresponds to production of reactive power.

B.2 Transmission Lines parameters

From	To	Line Number	Resistance (Ω)	Inductance (Ω)	Capacitance (μF)
1011	1013	1	1.69	11.83	0.26
1011	1013	2	1.69	11.83	0.26
1012	1014	1	2.37	15.21	0.34
1012	1014	2	2.37	15.21	0.34
1013	1014	1	1.18	8.45	0.19
1013	1014	2	1.18	8.45	0.19
1021	1022	1	5.07	33.80	0.57
1021	1022	2	5.07	33.80	0.57
1041	1043	1	1.69	10.14	0.23
1041	1043	2	1.69	10.14	0.23
1041	1045	1	2.53	20.28	0.47
1041	1045	2	2.53	20.28	0.47
1042	1044	1	6.42	47.32	1.13
1042	1044	2	6.42	47.32	1.13
1042	1045	1	8.45	50.70	1.13
1043	1044	1	1.69	13.52	0.3
1043	1044	2	1.69	13.52	0.3
2031	2032	1	5.81	43.56	0.1
2031	2032	2	5.81	43.56	0.1
4011	4012	1	1.6	12.8	0.4
4011	4021	1	9.6	96	3.58
4011	4022	1	6.4	64	2.39
4011	4071	1	8	72	2.79
4012	4022	1	6.4	56	2.09
4012	4071	1	8	80	2.98
4021	4032	1	6.4	64	2.39
4021	4042	1	16	96	5.97
4022	4031	1	6.4	64	2.39
4022	4031	2	6.4	64	2.39
4031	4032	1	1.6	16	0.6
4031	4041	1	9.6	64	4.77
4031	4041	2	9.6	64	4.77
4032	4042	1	16	64	3.98
4032	4044	1	9.6	80	4.77
4041	4044	1	4.8	48	1.79
4041	4061	1	9.6	72	2.59
4042	4043	1	3.2	24	0.99
4042	4044	1	3.2	32	1.19
4043	4044	1	1.6	16	0.6
4043	4046	1	1.6	16	0.6
4043	4047	1	3.2	32	1.19
4044	4045	1	3.2	32	1.19
4044	4045	2	3.2	32	1.19
4045	4051	1	6.4	64	2.39
4045	4051	2	6.4	64	2.39
4045	4062	1	17.6	128	4.77
4046	4047	1	1.6	24	0.99
4062	4063	1	4.8	48	1.79

From	To	Line Number	Resistance (Ω)	Inductance (Ω)	Capacitance (μF)
4062	4063	2	4.8	48	1.79
4071	4072	1	4.8	48	5.97
4071	4072	2	4.8	48	5.97

B.3 Transformers

HV-Busbar	LV-Busbar	Number	Rating (MVA)	HV (kV)	LV (kV)	ER12* (p.u)	EX12* (p.u)	Φ* (degrees)
4011	1011	1	1250	400	130	0.0	0.1	0
4012	1012	1	1250	400	130	0.0	0.1	0
4022	1022	1	835	400	130	0.0	0.1002	0
4031	2031	1	835	400	220	0.0	0.1002	0
4044	1044	1	1000	400	130	0.0	0.1	0
4044	1044	2	1000	400	130	0.0	0.1	0
4045	1045	1	1000	400	130	0.0	0.1	0
4045	1045	2	1000	400	130	0.0	0.1	0
4041	41	1	1000	400	130	0.0	0.1	0
4042	42	1	750	400	130	0.0	0.0975	0
4043	43	1	1500	400	130	0.0	0.105	0
4046	46	1	1000	400	130	0.0	0.1	0
4047	47	1	250	400	130	0.0	0.1	0
4051	51	1	1500	400	130	0.0	0.105	0
4061	61	1	750	400	130	0.0	0.0975	0
4062	62	1	500	400	130	0.0	0.1	0
4063	63	1	1000	400	130	0.0	0.1	0

ER12: Short circuit resistance between winding 1 and 2 in p.u of transformer base power and nominal voltage of the HV winding.

EX12: Short circuit reactance between winding 1 and 2 in p.u of transformer base power and nominal voltage of the HV winding.

Φ: Phase shift between 1st and 2nd winding in degrees.

B.4 Generators parameters

Name	Busbar	Rating (MVA)	Type	State	X_d (p.u)	X_q (p.u)	X_d' (p.u)	X_q' (p.u)	X_d'' (p.u)	X_q'' (p.u)	X_T (p.u)	X_A (p.u)	T_{d0}' (sec)	T_{q0}' (sec)	T_{d0}'' (sec)	T_{q0}'' (sec)	H (MWs/MVA))	$SE_q(1.0)$	$SE_q(1.2)$
442G1	4042	700	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
447G1	4047	600	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
447G2	4047	600	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
451G1	4051	700	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
451G2	4051	700	A	0	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
462G1	4062	700	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
463G1	4063	600	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
463G2	4063	600	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
142G1	1042	400	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
143G1	1043	200	A	1	2.2	2	0.3	0.4	0.2	0.2	0.15	0.15	7	1.5	0.05	0.05	6	0.1	0.3
411G1	4011	1000	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
412G1	4012	800	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
421G1	4021	300	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
431G1	4031	350	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
441G1	4041	300	C	1	1.55	1	0.3	-	0.2	0.2	0.10	0.15	7	-	0.05	0.1	2	-	-
471G1	4071	500	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
472G1	4072	4500	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
112G1	1012	800	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
113G1	1013	600	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
114G1	1014	700	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
121G1	1021	600	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
122G1	1022	250	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-
232G1	2032	850	B	1	1.1	0.7	0.25	-	0.2	0.2	0.15	0.15	5	-	0.05	0.1	3	-	-

Type: A (Round rotor generators in thermal power plants), B (Salient pole generators in hydro power plants), C (Salient pole synchronous compensator).
State: 1 (in operation), 0 (out of operation).
X_A: Stator leakage reactance.
Saturation Parameter: $SE_q(1.0)$, $SE_q(1.2)$

B.5 Power Control Generators

Busbar	Generator	Bus Type	Active Production (MW)	Voltage Set point (kV)	Q_{MAX} (MVar)	Q_{MIN} (MVar)
4011	411G1	Slack	-	404	-	-
4012	412G1	PV	600	404	400	-160
4021	421G1	PV	250	400	150	-30
4031	431G1	PV	310	404	175	-40
4041	441G1	PV	-	400	300	-200
4042	442G1	PV	630	400	350	0
4047	447G1	PV	540	408	300	0
4047	447G2	PV	540	408	300	0
4051	451G1	PV	600	408	350	0
4062	462G1	PV	530	400	300	0
4063	463G1	PV	530	400	300	0
4063	463G2	PV	530	400	300	0
4071	471G1	PV	300	404	250	-50
4072	472G1	PV	2000	404	1000	-300
1012	112G1	PV	600	146.9	400	-80
1013	113G1	PV	300	148.85	300	-50
1014	114G1	PV	550	150.8	350	-100
1021	112G1	PV	400	143	300	-60
1022	122G1	PV	200	139.1	125	-25
2032	232G1	PV	750	242	425	-80
1042	142G1	PV	360	130	200	-40
1043	143G1	PV	180	130	100	-20

B.6 Transformers' tap changers (Power Control)

HV-Bus	LV-Bus	Turn Ratio*	Phase Shift*
4011	1011	1.12	0
4012	1012	1.12	0
4022	1022	1.07	0
4031	2031	1.05	0
4044	1044	1	0
4045	1045	1	0
4045	1045	1	0
4041	41	1	0
4042	42	1	0
4043	43	1	0
4046	46	1	0
4047	47	1	0
4051	51	1	0
4061	61	1	0
4062	62	1	0
4063	63	1	0

* The turn ratio and phase shift angle are fixed.

B.7 Excitation System

Type of generator	Round Rotor (Thermal Plants)	Salient Pole (Hydro Plants)	Salient Pole (Synchronous Compensator)
K	120	50	50
T_A	0.10	0.20	0.20
T_B	50	20	20
T_C	0.10	0.10	0.10
Max	5.0	4.0	4.0
Min	0.0	0.0	0.0

B.8 Loads

Busbar	Active Consumption (MW)	Reactive Consumption (MVar)	MP*	NP*	MQ*	NQ*
4071	300	100	1	2	0.75	0
4072	2000	500	1	2	0.75	0
1011	200	80	1	2	0.75	0
1012	300	100	1	2	0.75	0
1013	100	40	1	2	0.75	0
1022	280	95	1	2	0.75	0
2031	100	30	1	2	0.75	0
2032	200	50	1	2	0.75	0
1041	600	200	1	2	0.75	0
1042	300	80	1	2	0.75	0
1043	230	100	1	2	0.75	0
1044	800	300	1	2	0.75	0
1045	700	250	1	2	0.75	0
41	540	128.28	1	2	0.75	0
42	400	125.67	1	2	0.75	0
43	900	238.83	1	2	0.75	0
46	700	193.72	1	2	0.75	0
47	100	45.19	1	2	0.75	0
51	800	253.22	1	2	0.75	0
61	500	112.31	1	2	0.75	0
62	300	80.02	1	2	0.75	0
63	590	256.19	1	2	0.75	0

MP: Active power voltage exponent

NP: Active power frequency exponent

MQ: Reactive power voltage exponent

NQ: Reactive power frequency exponent

Appendix C. M-file for Siirtoverkkomalli model

```
close all
%xInitial=xFinal;
%save Allbuses_With_all_Govornor_update xInitial
%Droop Setting
Nordic_N1_droop=1e-5; Nordic_N2_droop=1e-5; N_droop=1e-5; NE_droop=1e-
5;
NW_droop=1e-5;
%Mechanical power of Govornor Areas
NE_Pmec=0.12; CN_Pmec=0.6; N_Pmec=0.123; NW_Pmec=0.415;
N2_Pmec=0; N1_Pmec=0;

%Mechanical power in constant torque areas
SW_Pmec=0.158;    S_Pmec=0.403;    SE_Pmec=0.298;    CW_Pmec=0.355676;
CS_Pmec=0.238771;
C_Pmec=0.355; CE_Pmec=0.234; Nordic_S_Pmec=0; Nordic_C_Pmec=0;

%Generator reference voltages
SW_ref=1.012;
S_ref=1.005;SE_ref=1.015;C_ref=1.005;NW_ref=1.015;N_ref=1.005;
NE_ref=1.005;
Nordic_C_ref=1.015;Nordic_N1_ref=1.015;Nordic_N2_ref=1.015;Nordic_S_re
f=1.015;

%Series inductances
SW_inductance=0.063375;    C_inductance=0.2704;    N_inductance=0.4056;
Nordic_S_inductance=0.6;
Nordic_N_inductance=0.4056;
        %reactance calculation
SW_L=SW_inductance/(2*pi*50);               C_L=C_inductance/(2*pi*50);
N_L=N_inductance/(2*pi*50);
Nordic_S_L=Nordic_S_inductance/(2*pi*50);
Nordic_C_L=Nordic_N_inductance/(2*pi*50);

%Shunt Load Reactor
SW_LR=100; S_LR=0.01; SE_LR=100; CS_LR=100; CW_LR=0.006; C_LR=0.008;
CE_LR=0.0035;
CN_LR=0.03; NW_LR=0.03; N_LR=0.03; NE_LR=0.03;

%Limit control of govornor areas
 %NE Bus Details control
NE_valve_up_limit=1-NE_Pmec; NE_valve_low_limit=NE_Pmec*(-1);

%CN Bus details control
CN_integrator_up_limit=1-CN_Pmec; CN_integrator_low_limit=CN_Pmec*(-1);
CN_limiter_up_limit=3-CN_integrator_up_limit;    CN_limiter_low_limit=-
3+CN_integrator_low_limit;
%N Bus details control
N_valve_up_limit=1-N_Pmec; N_valve_low_limit=N_Pmec*(-1);
%NW Bus details control
NW_valve_up_limit=1-NW_Pmec; NW_valve_low_limit=N_Pmec*(-1);
%Nordic_N2 Bus details control
Nordic_N2_valve_up_limit=0.212-N2_Pmec;
Nordic_N2_valve_low_limit=N2_Pmec*(-1);
%Nordic_N1 Bus details control
Nordic_N1_valve_up_limit=0.212-N1_Pmec;
Nordic_N1_valve_low_limit=N1_Pmec*(-1);
```

Appendix D. M-file for Nordic 32 model

```
close all
%Droop Setting
%N32_Grp2_droop=1e-5; N32_Grp1_droop=1e-5;
N_droop=1e-5; NE_droop=1e-5;
NW_droop=1e-5;

%Mechanical power of Govornor Areas
NE_Pmec=0.12; CN_Pmec=0.6; N_Pmec=0.123; NW_Pmec=0.415;
N32_Grp1_Pmec=1e-5; N32_Grp2_Pmec=1e-5;

%Mechanical power in constant torque areas
SW_Pmec=0.158;     S_Pmec=0.403;     SE_Pmec=0.298;     CW_Pmec=0.355676;
CS_Pmec=0.238771;
C_Pmec=0.355; CE_Pmec=0.234; N32_Grp3_Pmec=1e-5; N32_Grp4_Pmec=1e-5;

%Generator reference voltages
SW_ref=1.012;
S_ref=1.005;SE_ref=1.015;C_ref=1.005;NW_ref=1.015;N_ref=1.005;
NE_ref=1.005;
N32_Grp3_ref=1.015;N32_Grp2_ref=1.015;N32_Grp1_ref=1.015;N32_Grp4_ref=
1.015;

%Series inductances
SW_inductance=0.063375;    C_inductance=0.2704;    N_inductance=0.4056;
%Nordic_S_inductance=0.6;
Nordic_N_inductance=0.4056;

%reactance calculation
SW_L=SW_inductance/(2*pi*50);               C_L=C_inductance/(2*pi*50);
N_L=N_inductance/(2*pi*50);
%Nordic_S_L=Nordic_S_inductance/(2*pi*50);
Nordic_C_L=Nordic_N_inductance/(2*pi*50);

%Shunt Load Reactor
SW_LR=100;  S_LR=0.01;  SE_LR=100;  CS_LR=100;  CW_LR=0.006;  C_LR=0.008;
CE_LR=0.0035;
CN_LR=0.03; NW_LR=0.03; N_LR=0.03; NE_LR=0.03;

%Limit control of govornor areas
 %NE Bus Details control
NE_valve_up_limit=1-NE_Pmec; NE_valve_low_limit=NE_Pmec*(-1);
%CN Bus details control
CN_integrator_up_limit=1-CN_Pmec; CN_integrator_low_limit=CN_Pmec*(-1);
CN_limiter_up_limit=3-CN_integrator_up_limit;    CN_limiter_low_limit=-
3+CN_integrator_low_limit;
%N Bus details control
N_valve_up_limit=1-N_Pmec; N_valve_low_limit=N_Pmec*(-1);

%NW Bus details control
NW_valve_up_limit=1-NW_Pmec; NW_valve_low_limit=N_Pmec*(-1);
%Nordic_N2 Bus details control
%Nordic_N2_valve_up_limit=0.212-N2_Pmec;
Nordic_N2_valve_low_limit=N2_Pmec*(-1);
%Nordic_N1 Bus details control
%Nordic_N1_valve_up_limit=0.212-N1_Pmec;
Nordic_N1_valve_low_limit=N1_Pmec*(-1);
```