TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

TUIRE KUJANSUU

INERTIA EMULATION CAPABILITY OF CONVERTER-CONNECTED WIND POWER PLANTS

Master of Science Thesis

Examiner: prof. Sami Repo
Examiner and topic approved on
1 March 2017

ABSTRACT

TUIRE KUJANSUU: Inertia Emulation Capability of Converter-Connected Wind Power Plants
Tampere University of Technology
Master of Science Thesis, 97 pages, 0 Appendix pages
October 2017
Master's Degree Programme in Electrical Engineering
Major: Power Systems and Market
Examiner: Professor Sami Repo

Keywords: inertia emulation, synthetic inertia, virtual inertia, converter-connected wind power plant, frequency stability, the Nordic power system

The increasing share of asynchronous generation, such as converter-connected wind power generation, in the Nordic power system results in decreasing system inertia. Consequently, the frequency deviations in severe faults increase which increases the risk of the frequency to fall below the first step of under-frequency load shedding. One option to retain the present system security and the frequency stability is the so-called inertia emulation capability of converter-connected wind power plants that could be used to support the power system during large under-frequency events. Also the concepts of *emulated inertia*, *synthetic inertia*, *synthetic inertial response, virtual inertia*, and *virtual inertial response* are used in the literature to describe this functionality that provides a temporary active power boost during an under-frequency event according to a frequency signal measured by the converter.

In order to study the performance of the inertia emulation in the Nordic power system and to sketch suggestions for the requirement setting dynamic simulations were executed. The simulations were run in PSS®E in a power system model representing the Nordic power system scenario in 2025. The wind power capacity equipped with inertia emulation was modelled utilizing a manufacturer-specific wind power plant model. Additionally, three types of power flow cases were used to study the effect of the inertia emulation function on the overall stability of the Nordic power system.

It was observed that the impact of inertia emulation on the power system substantially depends on the control method and its implementation as well as on the parametrization. The inertia emulation function can support the power system during under-frequency events when implemented and parametrized in an appropriate way. This denotes smooth recovery characteristics and an appropriate power boost percentage with relation to the power boost duration in order to avoid a secondary frequency nadir, for example. According to the study, for system security, the inertia emulation requirement should be formulated in detail if such functionality were required in the Nordic power system. In this connection, six new criteria for a possible inertia emulation requirement were found in addition to the eight criteria previously recognized by the two Canadian system operators currently stipulating inertia emulation from the converter-connected wind power plants in their systems. Moreover, any contradictions between the stability criteria studied (frequency stability, voltage stability, and the damping of inter-area power oscillations) were not discovered if properly parametrized.

TIIVISTELMÄ

TUIRE KUJANSUU: Suuntaajakytkettyjen tuulivoimalaitosten inertiaemulointitoiminto
Tampereen teknillinen yliopisto
Diplomityö, 97 sivua, 0 liitesivua
Lokakuu 2017
Sähkötekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Sähköverkot ja -markkinat
Tarkastaja: professori Sami Repo

Avainsanat: inertiaemulointi, synteettinen inertia, virtuaalinen inertia, suuntaajakytketty tuulivoimalaitos, taajuusstabiilius, pohjoismainen voimajärjestelmä

Epäsynkronisen tuotannon, kuten suuntaajakytketyn tuulivoimatuotannon, osuuden kasvu pohjoismaisessa voimajärjestelmässä johtaa järjestelmän inertian pienenemiseen. Tästä johtuen taajuuspoikkeamat mitoittavissa vioissa kasvavat, mikä vuorostaan kasvattaa riskiä, että taajuushäiriössä taajuus laskee alle automaattisen kuormanirtikytkennän ensimmäisen rajan. Yksi vaihtoehto tämänhetkisen käyttövarmuuden ylläpitämiseksi ja taajuusstabiiliuden säilyttämiseksi on hyödyntää suuntaajakytkettyjen tuulivoimalaitosten niin kutsuttua inertiaemulointitoimintoa tukemaan voimajärjestelmää merkittävän alitaajuushäiriön aikana. Myös seuraavia englanninkielisiä käsitteitä *emulated inertia*, *synthetic inertia*, *synthetic inertial response, virtual inertia*, ja *virtual inertial response* käytetään kirjallisuudessa käsitteen *inertia emulation* lisäksi kuvaamaan tätä toimintoa, jolla voidaan suuntaajan mittaaman taajuussignaalin perusteella aikaansaada hetkellinen pätötehotuki alitaajuushäiriössä.

Dynamiikkalaskentasimuloinnein tutkittiin inertiaemuloinnin suorituskykyä pohjoismaisessa voimajärjestelmässä sekä luonnosteltiin suosituksia inertiaemulointivaatimuksen asettelua varten. Simuloinnit toteutettiin PSS®E-ohjelmalla pohjoismaista voimajärjestelmää vuonna 2025 kuvaavalla järjestelmämallilla. Inertiaemulointitoiminnolla varustettu tuulivoimatuotanto mallinnettiin valmistajakohtaisella tuulivoimalaitosmallilla. Lisäksi kolmea erityyppistä tehonjakotapausta käytettiin tutkiessa inertiaemulointitoiminnon vaikutusta pohjoismaisen voimajärjestelmän kokonaisstabiiliuteen.

Havaittiin, että inertiaemuloinnin vaikutus voimajärjestelmään riippuu olennaisesti ohjaustavasta ja sen toteutuksesta sekä toiminnon parametrisoinnista. Inertiaemulointitoimintoa voidaan käyttää voimajärjestelmän tukemiseen alitaajuushäiriön yhteydessä, kunhan toiminto on toteutettu ja parametrisoitu tarkoituksenmukaisesti. Tämä tarkoittaa esimerkiksi sulavaa palautumisvaiheen aikaista käyttäytymistä sekä sopivaa lisätehoprosenttia suhteessa lisätehovaiheen kestoon, jotta toissijainen taajuushäiriönaikainen taajuuskuoppa voidaan välttää. Jos inertiaemulointitoimintoa vaadittaisiin pohjoismaisessa voimajärjestelmässä, tulisi kyseistä toimintoa koskeva vaatimus olla yksityiskohtaisesti muotoiltu. Tällä hetkellä kaksi kanadalaista siirtoverkonhaltijaa vaativat inertiaemulointitoimintoa suuntaajakytketyiltä tuulivoimalaitoksilta operoimissaan järjestelmissä. Tässä työssä löydettiin kuusi uutta kriteeriä mahdollisen inertiaemulointivaatimuksen varalle kahdeksan aiemmin Kanadassa tarpeelliseksi tunnistetun kriteerin lisäksi. Oleellista on myös, että työssä ei havaittu ristiriitoja tutkittujen stabiiliuskriteerien eli taajuusstabiiliuden, jännitestabiiliuden ja alueiden välisten tehoheilahtelujen vaimennuksen välillä, kun inertiaemulointitoiminto on parametrisoitu asianmukaisesti.

PREFACE

This M.Sc. Thesis was carried out for the Finnish national transmission system operator Fingrid Oyj. First of all, I would like to express my gratitude to Fingrid Oyj for this M.Sc. Thesis opportunity.

Secondly, I would like to thank the supervisor of my thesis M.Sc. (Tech.) Antti Harjula at Fingrid Oyj for the guidance throughout the process. Additionally, many thanks to the steering group for the interesting discussions and observations as well as for commenting on the work. I would also like to thank my colleagues both for helping me with various problems and for the great team spirit at the office.

The examiner of my thesis, Professor Sami Repo at Tampere University of Technology, I would like to thank for the valuable comments that often made me think from a new perspective.

Moreover, I would like to thank my family for the support they have provided throughout my studies. Finally, I thank you Arttu for always being there for me not only during this process but also throughout my studies.

Helsinki, 24.10.2017

Tuire Kujansuu

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
aFRR	Automatic Frequency Restoration Reserves
DFIG	Doubly-Fed Induction Generator
ENTSO-E	European Network of Transmission System Operators for Electricity
FFR	Fast Frequency Response
FC	Full Converter
FCR	Frequency Containment Reserves
FCR-D	Frequency Containment Reserves for Disturbances
FCR-N	Frequency Containment Reserves for Normal operation
FRR	Frequency Restoration Reserves
FRT	Fault Ride Through
HVDC	High Voltage Direct Current
IE	Inertia Emulation
IESO	Independent Electricity System Operator
IR	Inertial Response
mFRR	Manual Frequency Restoration Reserves
NA	Not Applicable
PSS®E	Power Transmission System Planning Software
RES	Renewable Energy Sources
RfG	Requirements for Generators
RoCoF	Rate of Change of Frequency
rpm	Revolutions per Minute
RR	Replacement Reserves
SONI	System Operator Northern Ireland
SPS	System Protection Scheme
TSO	Transmission System Operator
WECC	The Western Electricity Coordinating Council
WPP	Wind Power Plant
WRIG	Wound Rotor Induction Generator
WTG	Wind Turbine Generator

f	frequency
$f_{\mathrm{activation}}$	activation frequency
f_{g}	measured grid frequency
f_{gref}	nominal grid frequency
$f_{\mathrm{max\_boost}}$	frequency for maximum power boost
$f(t)$	frequency measurement
H	inertia constant of a synchronous machine
H_i	inertia constant of synchronous generator i
H_{sys}	aggregated inertia constant of the individual machines in the system
I_{S}	stator current
I_{R}	rotor current
J	moment of inertia of a synchronous machine
K_{f}	gain
P	active power
ΔP	active power imbalance
P_{boost}	power boost

$P_{\mathrm{boost\_percentage}}$	power boost percentage
P_{output}	active power output of a wind turbine generator
P_{r}	rated active power
P_{rated}	rated active power
$P_{r\mathrm{ef}}$	active power reference
$P(t\mathrm{=}0)$	active power output of a wind turbine generator at the moment when the inertia emulation function is activated
P_{WT}	wind turbine output power
S_{r}	rated apparent power of a machine
$S_{\mathrm{r}i}$	rated apparent power of synchronous generator *i*
t	time
T_{a}	accelerating torque
T_{e}	electromagnetic torque
T_{HPF}	time constant of a high-pass filter
T_{LPF}	time constant of a low-pass filter
T_{m}	mechanical torque
Q	reactive power
Q_{ref}	reactive power reference
U_{R}	rotor voltage
$\mathrm{U}_{\mathrm{ref}}$	stator voltage reference
U_{S}	stator voltage
W_{kin}	kinetic energy of a synchronous machine
β	pitch angle
β_{ref}	blade reference angle
θ_{gen}	generator rotor angle
ω_{gen}	rotational speed of generator rotor
ω_{m}	rotational speed of a rotor
$\omega_{\mathrm{m,r}}$	rated rotational speed of a rotor
ω_{turb}	rotational speed of a turbine

1. INTRODUCTION

This chapter introduces the background of the topic and the objectives of the thesis. The motivation and the structure of the thesis are described as well.

1.1 Background

In the Nordic power system, a considerable portion of conventional power generation based on synchronous generators has been replaced by asynchronous wind power generation in the past several years and the trend will continue. Therefore, the percentage of wind power generation of the total generation has increased and will increase even more. As the inherent inertia of a converter-connected wind power plant connected to the grid is zero, this change in power generation leads to a reduction of power system inertia which weakens the frequency stability of the system. As the total inertia of the system decreases, frequency deviations in severe faults, such as in sudden losses of power generating units, increase.

In addition, nuclear and hydro power both have a significant role in power generation in the Nordic power system. Nuclear power is characterized by large unit sizes. Therefore, a tripping of a nuclear unit results in a remarkable loss of active power causing a significant frequency disturbance event. Moreover, the inertia of hydro generators is lower than the inertia of steam generators used, for example, in gas and coal power plants. The significant share of hydro generation therefore denotes that the inertia of the Nordic power system is originally relatively low especially if the number of hydro generators connected to the grid is low.

Actions have to be taken in order to guarantee the frequency stability of the Nordic power system also in the future. One option to solve the future challenges of the minimum frequency reached during the frequency disturbance and the steepness of the fall in frequency both caused by low inertia is setting an inertia emulation requirement for converter-connected wind power plants. The converter-connected variable-speed wind turbine generators are namely capable of providing active power support during a short-duration under-frequency event by temporarily releasing additional active power drawn from the energy stored in the rotating masses of the wind turbine generator. The capability able to provide the active power support is known as inertia emulation.

1.2 Scope and objectives of the thesis

This thesis research is carried out for the Finnish national transmission system operator Fingrid Oyj (hereinafter Fingrid). The focus will be on studying the inertia emulation capability to support the Nordic power system during under-frequency events without the curtailment of wind power production. Moreover, since inertia market is not under the scope of this study, it is only mentioned briefly as an option for managing under-frequency events in power systems with low inertia. This thesis focuses on under-frequency events though the decreasing system inertia impacts also on the frequency deviations in over-frequency events.

The primary objective of this thesis is to study the performance of inertia emulation functionality of converter-connected wind power plants in the Nordic power system in order to investigate whether the inertia emulation is beneficial and accountable enough for the Nordic power system. Thus, the capacity of inertia emulating converter-connected wind power generation needed to maintain the frequency stability of the Nordic power system is studied. The most effective control method to improve the frequency nadir, which denotes the minimum instantaneous frequency, and to reduce the rate of change of frequency is analyzed, too. This thesis also aims to conclude suggestions how the inertia emulation requirement should be specified in case of deciding to require such performance.

To evaluate the performance of inertia emulation functionality and to define the possible suggestions for the inertia emulation requirement, this thesis also aims to cover the following questions grouped by the subject.

A) Availability and limitations of inertia emulation:

- What is the operating range in which the inertia emulation capability is available? In other words, what is the minimum percentage of rated active power so that the inertia emulation function can still be required?
- Is it possible to set the same requirement for both the Type 3 and 4 wind turbine generator technologies (see Section 3.2.1 for descriptions)?

B) Parametrization of inertia emulation:

- What is the impact of parameterization on the performance of inertia emulation?
- What is the impact of the additional active power on the performance of inertia emulation? How does the amount of additional active power effect on the recovery phase?
- What is the impact of the recovery phase duration on the performance of inertia emulation? How does it effect on the performance of inertia emulation if the recovery phase is prolonged?

C) Performance of inertia emulation in a power system with power oscillations:

- How do the power oscillations impact on the performance of the inertia emulation functionality with different control methods?

D) Consistency of inertia emulation with the selected stability criteria (frequency stability, voltage stability, and the damping of inter-area power oscillations):

- How do the different control methods impact on the selected stability criteria?
- Does inertia emulation cause contradictions between the selected stability criteria?

E) Consistency of inertia emulation with fault ride through function:

- Does the recovery time of the fault ride through function impact on the performance of inertia emulation? Are there contradictions between these functions?

1.3 Motivation

The inertia emulation capability of converter-connected wind power plants to support a power system during large under-frequency events has been studied for several years. As a result, the inertia emulation functionality is commercially available and it has been required for some years both in Hydro-Québec's and IESO's systems in Canada. Nevertheless, there have been some problems with the performance of the function though the function meets the present requirements. Especially the parts in the inertia emulation requirements concerning the recovery phase have proved crucial for the system stability as discussed in [2][4][13], for example. Namely, if the recovery characteristics are not smooth enough, there is a risk for a secondary frequency nadir caused by the active power reduction during the recovery phase. It is also known that the control method has a great impact on the inertia emulation. Though some of the results of the previous studies presented in the literature can be generalized, the function must be studied in the Nordic power system model separately in order to analyze the potential as well as the challenges of the function in the Nordic power system as also emphasized in the conclusions in [47].

This knowledge emphasizes TSO's responsibility to set the inertia emulation requirements properly to fit the specific power system needs. Also the implementations of the inertia emulation function must be further developed by manufacturers to be able to meet the future requirements that are expected to be tightened.

Previous research on the topic has focused either on studying inertia emulation from a theoretical perspective in a simplified power system model, or studying inertia emulation performance according to measurements from real power systems with an inertia emulation requirement in Canada, or studying how to design the inertia emulation controller. In [3] and [51], for example, the performance of inertia emulation was studied in a simplified Nordic power system model but the emphasis was on the inertia emulation control side.

In this thesis, the inertia emulation capability of wind power plants is studied in a detailed Nordic power system model with a manufacturer-specific wind power plant model for the first time. The detailed power system model utilized enables, for example, analyzing the effect of power oscillations on the performance of inertia emulation, and vice versa. Additionally, the utilization of a manufacturer-specific wind power plant model enables studying the challenges of the commercial functions available as well as the issues demanding consideration when setting an inertia emulation requirement. In this study, the influence of inertia emulation on frequency, voltage and rotor angle stability are analyzed, too. Moreover, the inertia emulation function is studied together with the fault ride through function in order to reveal possible contradictions between the functionalities.

1.4 Structure of the thesis

This thesis report consists of eight chapters and has the following structure.

Chapter 2 summarizes the theoretical background to understand the need for studying the inertia emulation capability in the Nordic power system. The chapter begins with a brief overview on the Nordic power system, and then, focuses on describing the frequency dynamics in the Nordic power system.

Chapter 3 concerns the frequency response and inertia emulation of wind power plants. In the chapter, the frequency response requirements of wind power plants in Finland are summarized whereas the inertia emulation capability is thoroughly described. Additionally, the performance of inertia emulation control method known as synthetic inertia in the Nordic power system is discussed according to the literature.

Chapter 4 presents examples on managing under-frequency events in power systems with low inertia. Some practices used in Canada, Ireland and Northern Ireland are studied and compared. Additionally, the performance of inertia emulation in a real power system is assessed according to the literature.

Chapter 5 describes the research methodology used in this study. More precisely this denotes describing the models as well as the simulation setup.

Chapter 6 presents and analyzes the simulations results. The inertia emulation control methods relative different stability criteria and their performance with different parameter settings are compared.

Chapter 7 summarizes the results of this thesis. The chapter also lists suggestions for inertia emulation requirement setting if such performance was required in the Nordic power system.

Chapter 8 draws the conclusions according to the results of this study. Finally, recommendations for future work are proposed.

2. FREQUENCY DYNAMICS IN THE NORDIC POWER SYSTEM

In this chapter the theoretical background of frequency dynamics focusing on the Nordic power system is reviewed. The chapter describes the Nordic power system and its frequency control as well as the definitions of stability and inertia among others.

2.1 Overview of the Nordic power system

The synchronous Nordic power system consists of the subsystems of Finland, Sweden, Norway and Eastern Denmark (Zealand) [28]. There are several interconnections between these synchronously operating transmission systems [28]. The Finnish transmission system, for example, is interconnected to the Swedish transmission system through two 400 kV alternating current (AC) connections [28]. There is also a 220 kV AC connection between Finland and Norway [28].

The Nordic power system is asynchronously connected via high voltage direct current (HVDC) interconnections with the Continental European transmission system and with the IPS/UPS transmission system (Russia, Belarus, and the Baltic countries) [28]. There are two HVDC links from Finland to Estonia and a connection from Finland to Vyborg in Russia. There are also HVDC connections from Sweden, Norway and Eastern Denmark to Western Denmark (Funen and Jutland) [28]. Moreover, there are HVDC connections from Sweden to Germany, Poland and Lithuania, and from Norway to the Netherlands [28]. Most of these connections are bidirectional which means that the power can be transferred through the connections in both directions. The Nordic power system as a part of the interconnected network of Northern Europe is shown in Figure 1.

The four national transmission system operators (TSOs) Energinet.dk, Fingrid, Statnett, and Svenska kraftnät are responsible for the cooperation of their transmissions systems in the Nordic power system. In order to maintain the system security in the Nordic power system, the same system security criterion, so called N−1 criterion, is used throughout the system [26]. According to the N−1 criterion, *"the elements remaining in operation within a TSO's control area after occurrence of a contingency are capable of accommodating the new operational situation without violating operational security limits"* [19][20]. This means that the power system must withstand a contingency causing, for example, a loss of an individual principal component that can be, for example, a power generating unit, a power line, a transformer, a bus bar, or even consumption [15]. The faults that cause a loss of an individual principal component are called dimensioning faults as they have considerable effects on the power system [15] and they must not cause secondary failures or an interruption either in power production or consumption [26].

Figure 1. *The Nordic power system as a part of the interconnected network of Northern Europe [17].*

Power generation has mostly been based on hydro power in Norway [53] as well as on hydro and nuclear power in Sweden [54] and Finland [35]. However, the Nordic power system will change significantly in the near future mainly as a response to the changes in climate policy [12]. The usage of renewable energy sources (RES) increases, and the share of wind power is expected to triple in 2010–2025, as for example [12] suggests. The Nordic TSOs have listed the main changes in the Nordic power system by 2025 which are

- the closure of thermal power plants,
- the increasing penetration of wind power,
- the decommissioning of Swedish nuclear power plants,
- the increase in the interconnector capacities between the Nordic power system and other systems [12].

The main challenges, arisen as a consequence of the issues in the list, contain the ensuring a good frequency quality and the adequate level of inertia among others [12].

As described more in detail in Section 5.1.1, the power system model used in the simulations in this thesis is based on the future scenario of the Nordic power system and represents the year 2025. Table 1 lists the annual key figures of the Nordic power system scenario for 2025. Also the historical data of 2013 is provided for the sake of comparison.

Table 1. *Annual key figures of the Nordic power system scenario for 2025 in comparison to historical data of 2013 [34].*

Key figure [TWh/year]	2013	2025
Nordic demand	383	411
Nordic wind production	23	59
Nordic solar production	0	2
Nuclear production in Sweden & Finland	86	85
Annual balance Nordic countries	±0	+13
Annual balance Sweden	+10	+18
Annual balance Finland [a]	−16 (−11)	−17 (−14)
Nordic system price [€/MWh] [b]	38	46
Share of RES generation	65%	73%
Share of CO2-free generation	88%	93%

[a] Balance including net flow between Russia and Finland given in parenthesis

[b] Average price for Sweden and Norway (normal hydro year) used to represent the system price for the scenarios, excluding inflation

2.2 Power system stability

Power system stability can be broadly defined as power system ability to remain operational equilibrium under normal operating conditions as well as to recover after a disturbance [46] (p. 19). Power system stability is a multidimensional issue as it is affected by numerous factors [46] (p. 34). The classification of power system stability presented in Figure 2 demonstrates the complexity of a power system stability problem. Since the power system stability is a combination of all the stability categories, it should be ensured that the improvement on one stability category is not performed at the expense of another [46] (p. 35).

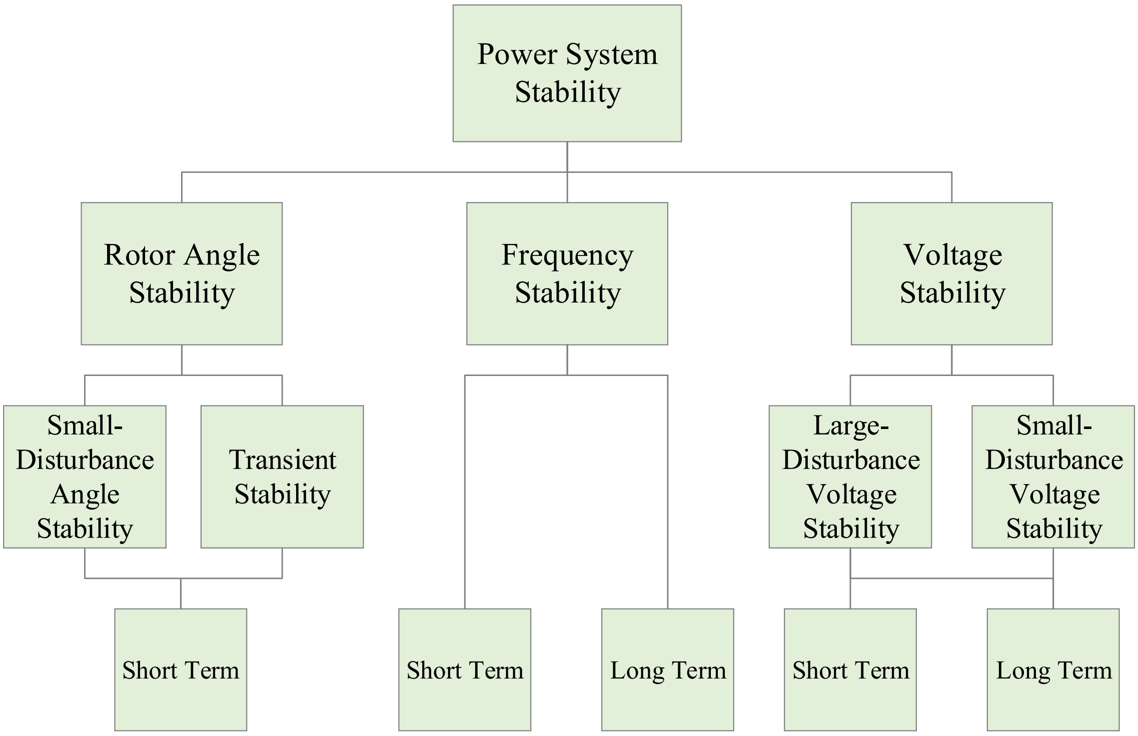

***Figure 2.** Classification of power system stability. Adapted from [45].*

As Figure 2 shows, power system stability can be divided into three main classes: rotor angle stability (also known as angular stability), frequency stability, and voltage stability. Rotor angle stability refers to the ability of synchronous generators to remain in synchronism [44]. Frequency stability is the power system ability to maintain the system frequency steady and close to nominal, whereas voltage stability is the power system ability to maintain steady bus voltages throughout the synchronous system [44].

The frequency stability of the Nordic power system is an important issue in this thesis since the inertia emulation capability studied in this thesis aims to improve the frequency stability of the Nordic power system. The impact of the inertia emulation on the overall power system stability is however evaluated by taking account of the following stability criteria: *frequency stability*, *voltage stability*, and *damping of inter-area power oscillations*, which is equal to small-disturbance angle stability after N−1 contingency.

2.3 Frequency dynamics

This section describes the basics of frequency control in the Nordic power system as well as the concept of inertia and its role in frequency disturbance events.

2.3.1 Power balance and frequency

Power system frequency is a measure reflecting the *power balance* that is the instantaneous balance between the active power production and consumption. The frequency remains constant when the active power production and consumption are equal. Power systems as well as electrical machines and other electrical appliances are designed to operate at a specific frequency and, for the sake of power system stability and security, it is desirable that frequency remains at or close to its nominal value. Therefore, the aim of the frequency control is to retain frequency reasonably close to its nominal value by balancing the active power production and consumption.

In practice, the frequency differs from the nominal value as the active power production and consumption are not equal. Whenever the frequency is decreasing, the consumption is higher than the production, and the other way around.

The frequency of a power system varies continuously. Traditionally, this is mainly due to the changes in the power consumption. In practice, the power generation varies, too. This originates from the wind and solar generation that are dependent on the weather and other constantly changing climatic issues as well as from the fluctuating processes on thermal power plants and the hour changes due to the trading period of one hour in the Nord Pool day-ahead market. However, slight frequency changes are acceptable and, for the system security, both the rate of the change and the absolute value of the change determine the severity of the variations in frequency. Over-frequency events can also be challenging for the power system but this thesis focuses on the measures that can be used in supporting the system during under-frequency events.

The nominal frequency of the Nordic power system is 50.0 Hz. The Nordic TSOs have agreed that the frequency in normal state should remain within a specific target area, namely within the range of 49.9–50.1 Hz [27]. The normal state denotes an operational state of the power system in which the power system is prepared to manage a dimensioning fault, the production meets the consumption, the frequency, voltage and transmission are within the limits, and the reserve requirements are met [14]. The Nordic TSOs utilize regulating bids at the power balancing markets and different types of reserves in order to keep the frequency close to nominal [27]. The reserve products utilized in Finland are described in Section 2.3.2.

2.3.2 Frequency containment reserves

The importance of frequency control was described above in Section 2.3.1. Fingrid and the other Nordic TSOs are responsible for ensuring the power balance and steady system frequency in the Nordic power system [27]. The TSOs acquire reserve products at different time scales in order to react to imbalances between consumption and production [27]. The reserve processes utilized to control the frequency can be classified as follows

1. Frequency Containment Reserves (FCR),
2. Frequency Restoration Reserves (FRR),
3. Replacement Reserves (RR) [23].

Frequency containment reserves are used to control the frequency and power balance constantly [23]. In other words, they are used to compensate momentary frequency deviations. The reserve process of frequency containment reserves is generally known as *primary frequency control*. Frequency restoration reserves aim to restore the frequency to the acceptable range after a disturbance [23]. Frequency restoration reserves also release the activated frequency containment reserves back into use [23]. In turn, replacement reserves would release the activated frequency restoration reserves so that they would be available if a new disturbance occurred [23]. However, replacement reserves are not utilized in the Nordic power system [23].

The four reserve products used in Finland are

1. Frequency Containment Reserves for Normal operation (FCR-N),
2. Frequency Containment Reserves for Disturbances (FCR-D),
3. Automatic Frequency Restoration Reserves (aFRR),
4. Manual Frequency Restoration Reserves (mFRR) [23].

Figure 3 presents the four reserve products as well as the time frames of their operation. Both FCR-N and FCR-D activate automatically by following the changes in the frequency [23]. FCR-N aims to maintain the frequency in the acceptable range of 49.9–50.1 Hz during the normal operation of the system, whereas FCR-D is utilized to compensate the active power deficit in frequency disturbance events caused by an unplanned disconnection of a generating unit, for example [22][30].

In the context of this thesis, the frequency containment reserves for disturbances are at the highest interest since the inertia emulation provided by the power control of converter-connected wind power plants (WPPs) would occur in the same time frame and they would both be activated due to a frequency disturbance. However, one should bear in mind that the frequency containment reserves for disturbances aim to balance the active power generation and consumption whereas the inertia emulation function would be used to manage the frequency disturbance which in practice denotes managing the steepness of the fall in the frequency and the minimum instantaneous frequency (see Section 2.3.4 for descriptions). This means that the objectives of the inertia emulation function and the frequency containment reserves for disturbances would be different. Additionally, the inertia emulation function in the Nordic power system would most likely be required to activate 2–4 s after the beginning of the disturbance event which means the activation time of the inertia emulation function would be shorter than the activation time of the frequency containment reserves for disturbances (see Table 2 for descriptions).

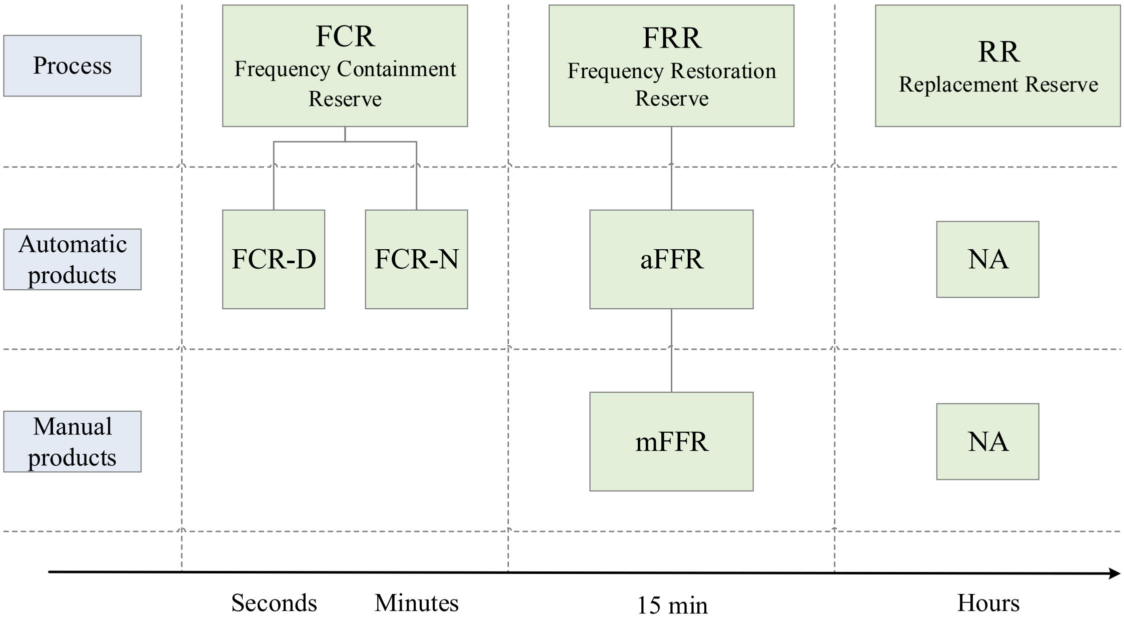

Figure 3. *Reserve products used in Finland. Replacement reserves are not applicable (NA) in the Nordic power system. Adapted from [23].*

Table 2 shows the most essential requirements for frequency containment reserves. See [21] and [31] for more precise descriptions. The frequency containment reserves for disturbances can be provided by production and load, for example [31].

Table 2. *Technical requirements for frequency containment reserve products [21][31].*

Product	Capacity of a bid	Requirements
FCR-N	0.1–5.0 MW	– Reserve shall regulate almost linearly within a frequency range of 49.90–50.10 Hz with the maximum dead band in frequency regulation of 50 ± 0.05 Hz. – 100% of the reserve capacity shall activate within 3 minutes after a frequency change of ±0.10 Hz.
FCR-D	1.0–10.0 MW	– Reserve shall regulate almost linearly so that activation begins when frequency falls below 49.90 Hz and 100% of the reserve capacity shall be activated at a frequency of 49.50 Hz. – 50% of the reserve capacity shall be activated in 5 seconds and 100% of the reserve capacity in 30 seconds with the frequency of 49.50 Hz.

2.3.3 System inertia

The frequency deviation caused by an imbalance between power production and consumption is related to the inertia of the power system [16]. The higher is the total inertia of the power system, the slighter is the frequency deviation in the system after being subjected to a disturbance. Inertia originates from kinetic energy and the total power system inertia derives from the kinetic energy stored in the electric rotating machines of synchronous turbine-generators and synchronous motors connected in the power system.

The kinetic energy of a synchronous machine in Ws at rated speed is given by

$$W_{\mathrm{kin}} = \frac{1}{2} J \omega_{\mathrm{m,r}}^2 \tag{1}$$

where J is the moment of inertia in kgm^2 and $\omega_{\mathrm{m,r}}$ is the rated rotational speed in mechanical rad/s [46]. Further, the inertia constant of a synchronous machine is defined as

$$H = \frac{W_{\mathrm{kin}}}{S_{\mathrm{r}}} = \frac{1}{2} \frac{J \omega_{\mathrm{m,r}}^2}{S_{\mathrm{r}}} \tag{2}$$

where W_{kin} is the stored kinetic energy at the rated speed in MWs and S_{r} is the rated apparent power of the machine in VA [46]. The inertia constant of a generator represents the time in seconds that the generator could supply power at its rated power if the power was merely supplied from the kinetic energy stored in the rotating masses of the generator at rated speed and if it was possible to the machine to supply its rated power from the kinetic energy of its shaft. Therefore, a power system of synchronous machines with higher inertia constants signifies a more robust system. The inertia constant varies typically between 1.0–10.0 s [46]. In contrast, the inertia constant of a converter-connected wind power plant is 0 s [12]. Table 3 presents the average inertia constants in the Nordic power system. The contribution of synchronous motors in the total system inertia of the Nordic power system is minor compared to the contribution of synchronous generators. Therefore, it is relevant that the table focuses on the generation.

Table 3. *Average inertia constants in the Nordic power system [16].*

Production type	**Inertia constant *H* [s]**
Nuclear	6.3
Other thermal	4.0
Hydro conventional	3.0
Hydro small-scale	1.0
Wind	0

In this context, it is practical to introduce the swing equation (or the equation of motion), too. The swing equation representing the dynamic behavior of synchronous machines is defined as

$$J \frac{d\omega_{\mathrm{m}}}{dt} = T_{\mathrm{a}} = T_{\mathrm{m}} - T_{\mathrm{e}} \tag{3}$$

where J is the moment of inertia in kgm^2, ω_{m} is rotational speed of the rotor in mechanical rad/s, t is time in s, T_{a} is accelerating torque in Nm, T_{m} is mechanical torque in Nm and

T_e is electromagnetic torque in Nm [46]. The values of T_m and T_e are positive for generators and negative for motors [46]. An imbalance between the mechanical and electromagnetic torques causes the electric rotating machine either to accelerate or decelerate [46]. A generator accelerates as the electrical torque is lower than the mechanical torque, and vice versa. When the both sides of the swing equation are multiplied by the mechanical rotational speed ω_m, it results in

$$J\omega_\mathrm{m}\frac{d\omega_\mathrm{m}}{dt} = P_\mathrm{m} - P_\mathrm{e} \tag{4}$$

where P_m and P_e are the mechanical power input and electrical power output [44].

When a large power generating unit or an importing HVDC interconnector from another synchronous system trips from the power system, it results in a significant active power deficit and the system frequency starts to decrease. Consequently, the synchronous generators connected to the system react to the frequency decrease. More precisely, the mechanical rotational speeds of turbine-generator rotors ω_m decelerate [12]. The deceleration releases kinetic energy stored in the rotors into the power system reducing the active power deficit [12]. However, as the rotational speeds of the synchronous generators decrease, the system frequency begins to decrease [12]. This immediate power response from kinetic energy of synchronous generators is known as *inertial response* or *synchronous inertial response*. In contrast to ordinary uncontrolled synchronous electric machines, the active power output of the reserves is controlled by the frequency, instead of the accelerating torque T_a caused by the frequency deviation, since their function is to help to maintaining the frequency close to the nominal value [12].

Through the inertial response of the synchronous electric machines, the system inertia has a significant role in the frequency response. The system inertia measured in MWs is given by

$$S_\mathrm{r}H = S_\mathrm{r1}H_1 + S_\mathrm{r2}\,H_2 + \cdots + S_\mathrm{rN}\,H_N \tag{5}$$

where $S_{\mathrm{r}i}$ is the rated apparent power and H_i is the inertia constant of synchronous generator i connected to the system [3].

At present, the total inertia capacity of the Nordic power system is in the order of 390 GWs [16]. In 2025, the system inertia is expected to be reduced to 315 GWs [12]. However, the situations with the lowest inertia levels are critical for frequency stability. It is estimated that the system inertia of 120–145 GWs is required in order to avoid the risks related to a disconnection of a large generation unit [12]. According to the estimations, the total inertia of the Nordic power system will be below this level 1–19% of the time in 2025 [12].

2.3.4 Frequency disturbance events

Under-frequency events are typically caused by a loss of a power generating unit or an importing HVDC interconnector from another synchronous system. For example, according to a frequency quality study regarding the Nordic power system in 2015, significant under-frequency events, in which the frequency is more than 0.3 Hz below the nominal, were often been caused by a disconnection of a nuclear unit [25]. In turn, according to a corresponding study for 2016, the frequency deviations exceeding the limit were most often caused by failures in HVDC interconnectors [24].

There are two essential concepts that are used to describe frequency deviations: the rate of change of frequency (RoCoF) and the frequency nadir. *RoCoF* is defined as

$$\text{RoCoF} = \frac{df}{dt} = \frac{\Delta P}{2H_{\text{sys}}} \tag{6}$$

in which f is the system frequency, t is time, ΔP is the active power imbalance, and H_{sys} is the aggregated inertia constant of the individual machines in the power system [18]. As can be seen from the equation above, RoCoF is related to the total power system inertia as well as to the size of the imbalance. In case of under-frequency event, the value of RoCoF denotes to the steepness of the fall in the frequency. In turn, *frequency nadir* refers to the minimum instantaneous frequency reached during the under-frequency event [18]. According to the knowledge acquired through experience, the frequency nadir in the Nordic power system is typically reached 5–8 s after the disturbance.

As explained above, it is crucial for the reliable operation of a power system that the system frequency remains close to nominal. A protection scheme known as under-frequency load shedding (UFLS) can be utilized in order to terminate a fast decline of frequency so that the system would remain operational [12][46]. Thus, the UFLS is meant to activate exclusively in the most severe disturbances. Load shedding in general denotes either automatic or manual disconnection of consumption [14]. In the Nordic power system, the UFLS is divided in steps and the frequency limit of the highest load-shedding step is 48.8 Hz [12]. If the power system inertia is too low, the RoCoF is high and, consequently, the frequency decreases too fast which means that the first frequency limit of UFLS is reached before the frequency containment reserves have reacted sufficiently [12]. Therefore, either the power system inertia must kept high enough or the highest dimensioning fault must be limited or the activation time of the frequency containment reserves must be shortened.

Figure 4 shows an example on the Nordic power system frequency response after the disconnection of a power generating unit. The RoCoF and the frequency nadir (minimum instantaneous frequency) are also pointed in the figure. A frequency response can be described in three time frames. The first stage (approximately 25–30 s in Figure 4) begins as the generating unit trips from the system [2]. The stage lasts a few seconds [2]. During this stage, the frequency response is determined by the inertial response from the synchronous generators [2]. During the second stage (approximately 30–110 s in Figure 4), the response from the reserves first start to decelerate the frequency decrease, and then contribute in frequency recovery [2]. The third stage begins (approximately at 110 s in Figure 4) as the frequency reaches its steady state value [2].

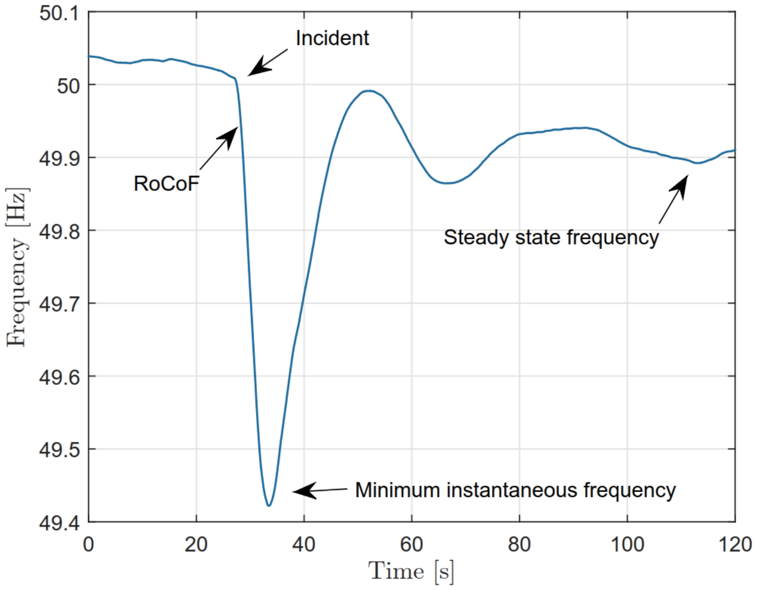

Figure 4. *Example of the frequency response of the Nordic power system after a disconnection of a generating unit [18].*

There are several factors affecting on the severity of an under-frequency event caused by a disconnection of a large generating unit or an importing HVDC interconnector from another synchronous system, for example. The four most influential factors are

- the amount of disconnected power,
- the system inertia,
- the load self-regulation,
- the amount and behavior of the frequency containment reserves [12].

The impact of these factors in under-frequency events is described next. The amount of disconnected power denotes the size of the disturbance. The higher the amount of the disconnected power is, the higher the active power deficit is, and the more significant frequency deviation is expected, if the other factors do not change. As explained above, the system inertia and the RoCoF are interrelated. The decrease in the system inertia increases the RoCoF which means that the frequency declines faster and the frequency containment reserves have lesser time to react before the frequency falls below a critical limit. The load self-regulation, also known as load frequency dependence or frequency dependence of consumption, denotes the feature of some motor loads which causes the load naturally to decrease as the frequency decreases. In 2025, the contribution of the load self-regulation in the Nordic power system is estimated to be in the order of 0.75 %/Hz [12].

Thus, the load self-regulation supports the system when the frequency decreases. The behavior of the frequency containment reserves, such as the activation time of the reserves, effects on the frequency response during an under-frequency event. Naturally, the faster the frequency containment reserves react, the better the frequency decline is managed. However, the initial RoCoF is always determined by the system inertia [12] and the size of the imbalance.

Figure 5 shows a) the impact of the system inertia on the frequency response after a disconnection of a generating unit and b) the power responses from inertia, frequency containment reserves, and load self-regulation. The figure demonstrates the connection between the system inertia and the behavior of frequency through the RoCoF and frequency nadir (minimum frequency).

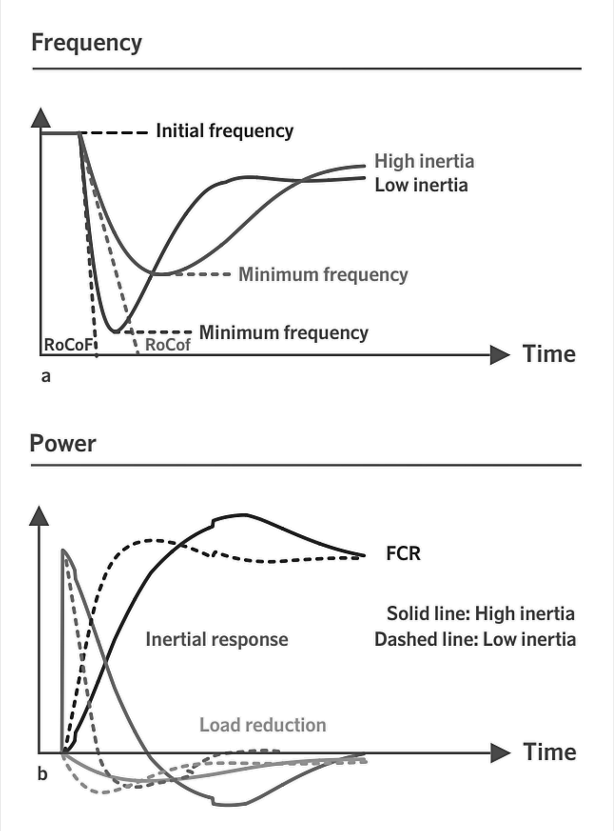

Figure 5. *Impact of inertia on frequency and power responses after a disconnection of a generator. a) Frequency responses with high and low inertia, and the corresponding RoCoF values. b) Power responses from inertia (synchronous inertial response), FCR and load reduction. Adapted from [12].*

In the case of low inertia, the response of the frequency containment reserves is faster than in the case of high inertia. This is owing to the faster frequency decline in the case of low inertia because then the governors detect the frequency deviation earlier, and consequently, the reserves react faster. The activation speed is not only a result of the frequency error seen by the governor but the mechanical equipment involved in the regulation restricts the activation speed that is possible to achieve. However, limits set by mechanical equipment are typically not reached during actual frequency disturbances.

2.4 Justification for reacting on low system inertia

Power system inertia is connected with the frequency stability of a power system by its relation to RoCoF. This is the main reason why the declining system inertia is considered as one of the main future challenges in the Nordic power system [12]. Therefore, providing supplementary inertia or other measures may be necessary to manage the change.

The Nordic power system is designed and operated according to the N−1 criterion, as discussed above in Section 2.1. It means that the power system must manage a single dimensioning fault. Therefore, TSOs need to set requirements for the operational performance that the power plants connected to the TSO's grid must fulfill. These requirements often belongs to grid codes. The unofficial translation of Fingrid's operative grid code for generators is called *Specifications for the Operational Performance of Power Generating Facilities VJV2013* [32], as the official version of the grid code is collected in Finnish in *Voimalaitosten järjestelmätekniset vaatimukset VJV2013* [33]. Fingrid's grid code for generators applicable to wind power plants from the perspective of frequency response is summarized in Section 3.1.

With respect to power system security, the generating units should support the power system stability during a fault. Moreover, according to Requirements for Generators (RfG) published by European Network of Transmission System Operators for Electricity (ENTSO-E), the European TSOs are allowed to require inertia emulation functionality from converter-connected wind power plants [19]. Therefore, it would be possible for Fingrid to set an inertia emulation requirement for converter-connected wind power plants.

However, requiring inertia emulation functionality from wind power plants is only one of the several solutions for managing under-frequency events in low inertia situations. The Nordic TSOs have listed solutions in a report [12]. The possible solutions can be divided in two groups: solutions to be implemented by the TSOs and solutions requiring broader collaboration between the power market participants [12].

Possible solutions to be implemented by the TSOs contain 1) setting requirements for minimum system inertia and 2) limiting the power output of the largest units, referring to both generators and import through HVDC links, in situations in which system inertia is low [12]. The idea of these possible solutions is to ensure that the power system withstands the dimensioning fault as the N−1 criterion requires.

Possible solutions that require cooperation between the power market participants are divided into short term and long term options [12]. In the short term, the inertia per generated power could be increased by running generation units with inertia with lower average power output [12]. Namely, the inertia of a synchronous generator is not effected by its power output but by the product of the rated power and the inertia constant, and the system inertia is the sum of the corresponding products that represent all the synchronous generators connected in the system (see Equation 5 in Section 2.3.3). There are more options applicable in the long term. They include enhancing the frequency containment reserves by either increasing the amount of the reserves or increasing the reaction speed of the reserves in order to achieve a faster response during a disturbance [12]. Low inertia could also be managed in the long term by installing system protection schemes (SPS), using HVDC links connected to other synchronous areas, adding rotating masses, such as synchronous condensers, to the system, or adding synthetic inertia (including inertia emulation of wind power plants) to the system [12]. The maximum effective disconnected power can be limited by a system protection scheme that disconnects predetermined amount of predetermined load when the pre-defined triggering disconnection event occurs [12].

The solutions listed above can also be divided by their effect on the electricity market. The day-ahead market of the Nordic power system and its principles are changed if the power output of the largest units is limited or if the TSOs dictate which units shall be connected to the system, for example. These type of changes in the electricity market can be avoided by using synchronous condensers, HVDC links or inertia emulation of wind power plants.

3. FREQUENCY RESPONSE AND INERTIA EMULATION

This chapter describes the frequency response of wind power plants. First, Fingrid's current frequency response requirements for wind power plants and the technologies of converter-connected wind power plant are explained briefly. Thereafter, the focus is on the inertia emulation capability.

3.1 Frequency response requirements in Fingrid's grid code

Fingrid's grid code for generators concern power generating units with rated active power capacity of 0.5 MW or higher [32][33]. In Fingrid's grid code for generators in force, power generating facilities are classified into four power classes by the rated active power P_r of the facility [32][33]. The power classes are presented in Table 4. The inertia emulating wind power plants studied in this thesis represent Power Classes 3 and 4 as the rated active power of the wind power plants vary from 40 MW to 200 MW. Therefore, the following summary involves wind power plants of Power Classes 3 and 4. Merely the most essential parts of the requirements related to frequency response are described.

Table 4. *Power classes of power generating units in Finland [32][33].*

Power class	Rated active power capacity
1	0.5 MW ≤ P_r < 10 MW
2	10 MW ≤ P_r < 25 MW
3	25 MW ≤ P_r < 100 MW
4	P_r ≥ 100 MW (or P_r ≥ 10 MW)[a]
[a] Facilities connected to the network located beyond the Isoniemi and Kokkosniva feeder bays of the Valajaskoski and Pirttikoski 220 kV substations	

The operational requirements applicable to wind power plants in Fingrid's grid code for generators are classified into three groups as follows

1. frequency control and active power control,
2. reactive power capacity,
3. voltage control and reactive power control [32][33].

In this connection, it is reasonable to focus on the operational requirements of frequency and active power control next since the inertia emulation would change the current frequency response required from wind power plants in Fingrid's grid code for generators.

First of all, the wind power plants representing Power Classes 3 and 4 must be able to adjust their active power according to the frequency measurement [32][33]. The droop of frequency control must be linear and adjustable [32][33]. Additionally, it is required that the rate of change of active power can be restricted and the active power can be curtailed [32][33]. It must also be possible to control the active power to decrease from full power to 20% of rated active power under 5 s [32][33]. The accuracy of 1 MW for the reference of active power control and the sensitivity of 10 mHz with maximum reaction time of 2 s for frequency control are required [32][33].

At present, the wind power plants are not required to continuously adjust their active power [32][33]. Fingrid can, however, stipulate the wind power plants to operate as the frequency and active power control requirements presume if the restoration of the power system to normal state after a disturbance requires such performance [32][33]. If Fingrid set an inertia emulation requirement, the wind power plants would not be required to constantly control their active power either. In that case, the wind power plants would be required to provide a temporary frequency response whenever the frequency falls below a pre-defined limit during an under-frequency event.

3.2 Inertia emulation capability of wind power plants

The inertia emulation capability of converter-connected wind power plants is described in this section.

3.2.1 Converter-connected wind power plants

All recent and new wind power installation connected to the Nordic power system represent Type 3 and Type 4 wind turbine generator technologies. Type 3 and 4 wind turbine generators (WTGs) represent the modern variable-speed wind turbine generators in which either a partial-scale or a full-scale converter decouples the wind turbine generator from the grid. Type 3 wind turbine generators represent the configuration with a partial-scale converter as shown in Figure 6, whereas Type 4 wind turbine generators are equipped with a full-scale converter as shown in Figure 7. These converter-connected wind power plants are capable of providing temporary active power boost, called inertia emulation in this thesis, during under-frequency events by adjusting their converter controls if the needed control systems are initially installed. The implementation of a new control system with an inertia emulation function would, in practice, mean updating the converter software.

The rough configuration of Type 3 wind turbine generator includes a gearbox, a wound-rotor induction generator (WRIG), and a partial-scale converter in addition to the actual wind turbine consisting of the tower, rotor and nacelle [1]. This technology is generally known as a doubly-fed induction generator (DFIG) [1]. Though Type 3 wind turbines are considered variable-speed turbines, the speed range is typically limited from −40% to +30% of the synchronous speed [1].

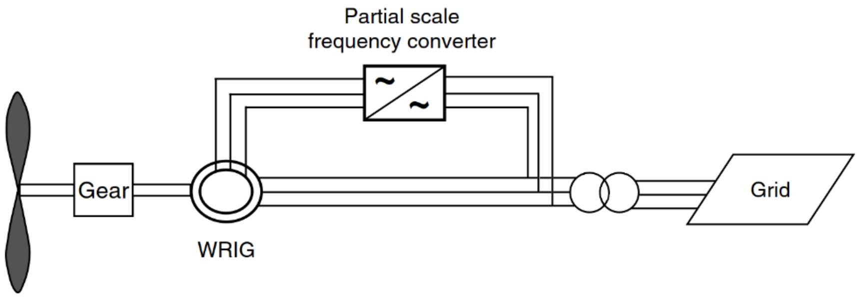

Figure 6. Configuration of Type 3 WTG. WRIG = wound-rotor induction generator. Adapted from [1].

In Type 4 wind turbine generators a full-scale converter decouples the generator and the grid [1]. The wind turbine generators representing the Type 4 technology are often called full converter (FC) wind turbine generators. A gearbox is not necessarily needed in the configuration that is emphasized by the dashed line around the gearbox [1].

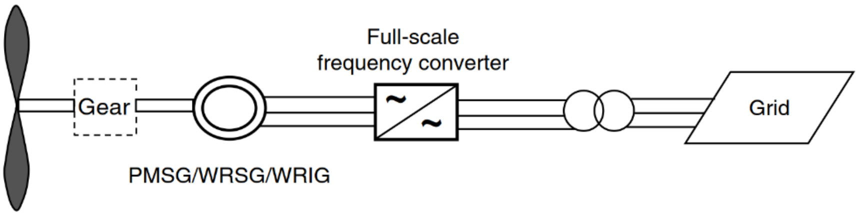

Figure 7. Configuration of Type 4 WTG. PMSG = permanent magnet synchronous generator, WRSG = wound-rotor synchronous generator, WRIG = wound-rotor induction generator. The dashed line around the gearbox denotes that the gearbox is not necessarily needed. Adapted from [1].

A wind turbine generator model typically consists of the following or similar elements:

- aerodynamic model representing the wind turbine rotor,
- mechanical model,
- generator drive model,
- pitch control system (also known as pitch servo),
- wind turbine control system,
- wind turbine protection system [1].

Figure 8 demonstrates a block diagram of a generic wind turbine generator model. The main controls of the wind turbine generator, such as active power control, is modeled by the wind turbine control system [1].

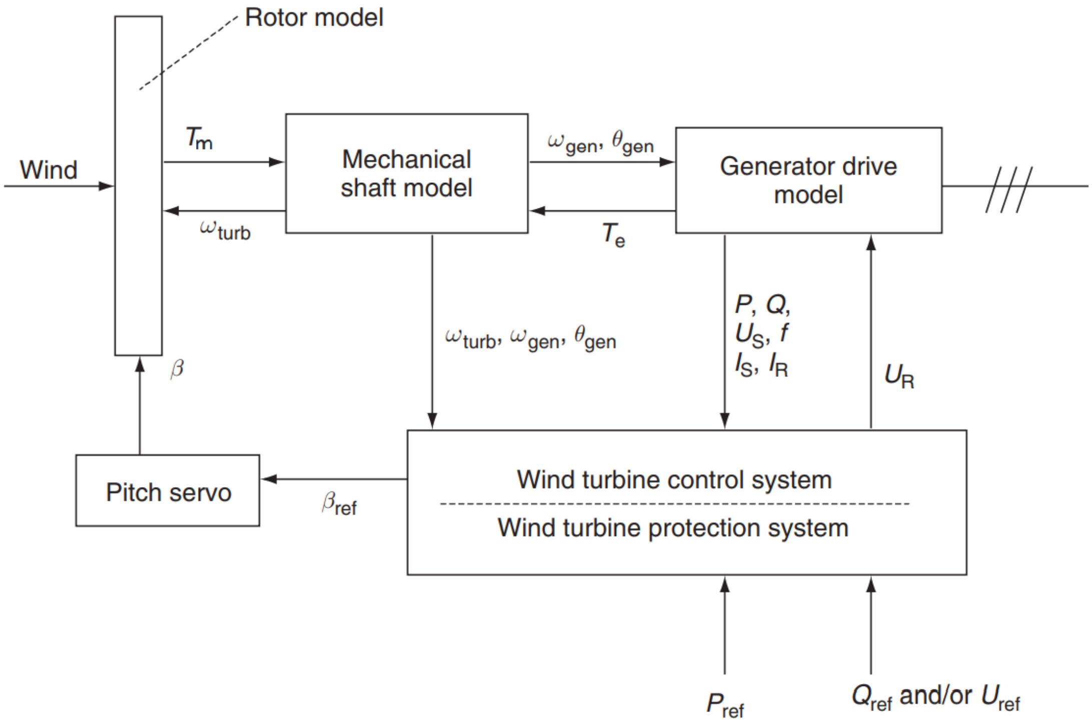

Figure 8. *Block diagram of a generic wind turbine generator model. f = grid frequency,* I_S *= stator current,* I_R *= rotor current, P = active power,* P_{ref} *= active power reference, Q = reactive power,* Q_{ref} *= reactive power reference,* U_S *= stator voltage,* U_R *= rotor voltage,* U_{ref} *= stator voltage reference,* T_e *= electromagnetic torque,* T_m *= mechanical torque,* ω_{turb} *= rotational speed of turbine,* ω_{gen} *= rotational speed of generator rotor,* θ_{gen} *= generator rotor angle,* β *= pitch angle,* β_{ref} *= blade reference angle. Adapted from [1].*

As mentioned above, the inertia emulation function would be controlled by the converter controls. The converter controls are included in the wind turbine control system (see Figure 8). The inertia emulation control methods are described in Section 3.2.3.

3.2.2 Inertia emulation

The wind power plants are typically divided in four groups by their technologies. Type 3 and 4 technologies represent the converter-connected wind turbine generators, as explained in Section 3.2.1. The power electronic converters of Type 3 and Type 4 wind turbine generators decouple the wind turbine generator and the grid. This means that the kinetic energy stored in the rotating masses of the wind turbine is also decoupled so that the wind power plant cannot provide a direct inertial response [1]. Thus, the inertia constant of a converter-connected wind power plant is 0 s [12], as mentioned in Section 2.3.3.

However, the converter controls of the wind power plants can be adjusted to emulate to some extent the inertial response of synchronous machines as it is described in the literature, in [1][2][3] for example, as well as required and utilized in real networks in Québec

[40] and Ontario [13][41] in Canada. The concept of *inertia emulation* (IE) denotes a functionality of a converter-connected wind power plant that provides a temporary active power boost during an under-frequency event according to a frequency signal. Also the concepts of *emulated inertia*, *synthetic inertia*, *synthetic inertial response, virtual inertia* and *virtual inertial response* are used in the literature. However, this thesis follows the definition of synthetic inertia described in [18] whereby the contribution of synthetic inertia is proportional to the RoCoF similarly to the synchronous inertial response. The power boost of inertia emulation namely is not necessarily proportional to the RoCoF, as it is explained in Section 3.2.3.

The additional active power of the power boost providing the inertial response is drawn from the kinetic energy stored in the rotating masses of the wind turbines, as explained in [2][36], for instance. Above the nominal wind speed of the wind turbine generator, the additional active power can directly be drawn from the wind without decelerating the rotor speed [2][10][36]. This is possible by reducing the pitch angle of the wind turbine blades [2][10][36]. Therefore, there is no need to restore the rotational speed and the power output after the deactivation of the power boost [2][10][36]. However, below and at the nominal wind speed, the inertia emulation functionality can be divided into two phases: *power boost phase* and *recovery phase*, also known as recovery period. The provision of power boost decelerates the rotational speed of the wind turbine rotor and, therefore, the active power output during the so-called recovery phase is lower than before the activation of the inertia emulation functionality [2][36]. During the recovery phase, the rotational speed is accelerated back to optimal that is determined by the prevailing wind speed [2][36]. Figure 9 presents an example of an ideal inertia emulation performance.

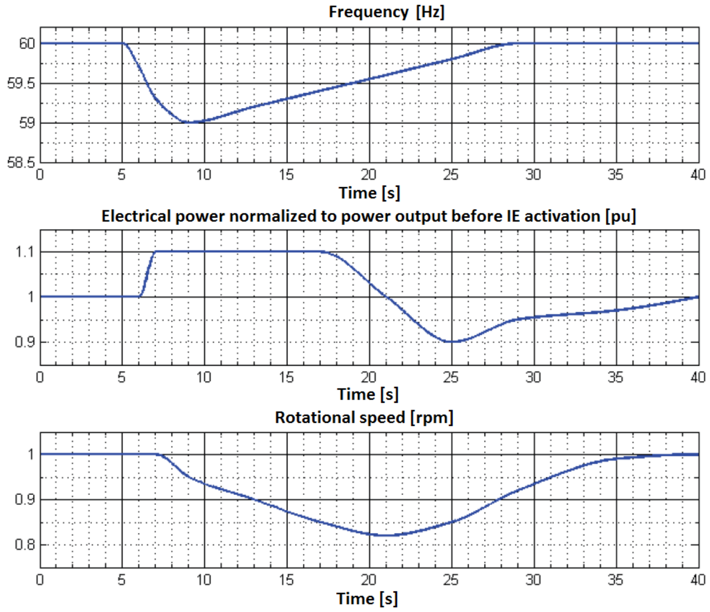

Figure 9. *Example of an ideal inertia emulation performance in a power system with nominal frequency of 60 Hz. IE = inertia emulation. Adapted from [36].*

The recovery phase follows the deactivation of the active power provision. As described above, the active power output of the wind power plant decreases during the recovery phase as the rotor rotational speed is accelerated back to optimal. Therefore, especially the parameters determining the recovery characteristics are critical for inertia emulation functionality. However, there are also several variables that determine the precise reduction in the active power in addition to the parametrization [2]. From this point of view, the initial power level before the activation of active power boost, the amount of active power boost, and prevailing wind conditions during the recovery phase are the most influential ones [2].

In general, inertia emulation can be used to improve the RoCoF or the frequency nadir or both. However, the usefulness of inertia emulation depends on many things. Due to the recovery phase, the utilization of inertia emulation, can delay the frequency recovery [57], for example. Additionally, the active power drop during the recovery phase can cause a secondary frequency nadir as explained in [2] and [4], for example.

The inertia emulation function is controlled by the converter controls, as discussed in Section 3.2.1. The converters of the wind turbine generators are typically slightly oversized, and thus, it is from the electrical side possible for the wind turbine generators to deliver a power boost of 10% of rated power for 10 s in all operating points [3][38][50]. As it is later discussed in Section 3.2.5, the restrictions of the power contribution during the power boost phase originate from the aerodynamic side of the wind turbine generator [38][50].

At present, several wind turbine generator manufacturers, such as Enercon [2][8], General Electric [2][37], Nordex [49], Senvion [2], Siemens [2], and Vestas [2] have a commercial product of inertia emulation available. Thus, the lack of commercial products of inertia emulation is not a hindrance for the inertia emulation requirement setting. Additional studies as well as operational experience on inertia emulation are however needed for acquiring a better understanding on the function. By December 2017, there will be wind turbine generators from five different manufacturers providing under-frequency support in Hydro-Québec's system in Canada [2]. From scientific perspective, this enables a broader analysis on the operational differences of manufacturer-specific inertia emulation functions in the future, for example.

3.2.3 Control methods

Three main control methods are presented in the literature for the inertia emulation of converter-connected wind power plants:

1. fixed power boost,
2. power boost proportional to absolute frequency (change),
3. synthetic inertia.

The differences between these methods are in the inputs of the power boost as well as in the provision of the power boost. As the following text describes more precisely, the active power contribution can be either fixed, proportional to frequency (change) or proportional to the derivative of the frequency (RoCoF). Moreover, it is also possible to use the combinations of the methods.

Fixed power boost refers to a control method which the power contribution is a fixed percentage either of the pre-disturbance active power output, the active power output before inertia emulation activation or of the rated active power. The power contribution duration is typically fixed, too. Thus, the power boost is independent of the frequency or its derivative meaning that the power boost does not adapt to a disturbance event. The power boost phase begins as the grid frequency falls below the pre-defined activation frequency (also known as frequency threshold) or dead band. Figure 10 shows an example of the control block diagram of fixed power boost.

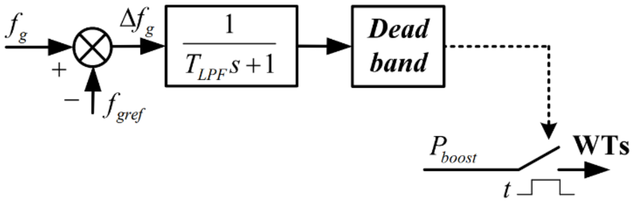

Figure 10. Control block diagram of fixed power boost. f_g = measured grid frequency, f_{gref} = nominal grid frequency, T_{LPF} = time constant of (low-pass) frequency filter, P_{boost} = power boost. Adapted from [52].

The active power contribution of inertia emulation can also be proportional to the absolute frequency change Δf. Then, the additional active power is linear to the grid frequency. The power boost phase begins as the grid frequency falls below the pre-defined activation frequency or dead band. An example of the control block diagram of proportional power boost is demonstrated in Figure 11.

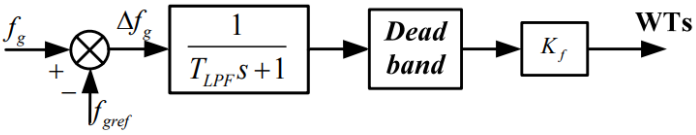

Figure 11. Control block diagram of power boost proportional to frequency change. f_g = measured grid frequency, f_{gref} = nominal grid frequency, T_{LPF} = time constant of (low-pass) frequency filter, K_f = gain. Adapted from [52].

Synthetic inertia denotes an inertia emulation control method that emulates the inertial behavior of the conventional synchronous generators as the additional active power is proportional to the frequency derivative *df/dt*, also known as the RoCoF, and the power contribution is instant. Figure 12 presents an example of the control block diagram of synthetic inertia. The control method of power boost proportional to frequency derivative can be considered as a variant of synthetic inertia. Namely, if a frequency threshold or a dead band is used to adjust the activation of the power boost phase of the function, it may more reasonable to use the concept of power boost proportional to frequency derivative to describe the control method since then the response does not imitate the synchronous inertial response as explained above in Section 3.2.2.

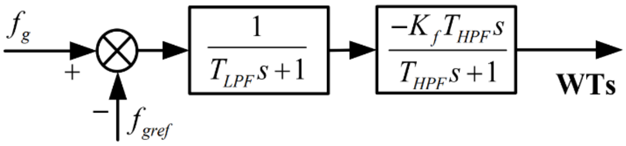

Figure 12. *Control block diagram of synthetic inertia. f_g = measured grid frequency, f_{gref} = nominal grid frequency, T_{LPF} = time constant of (low-pass) frequency filter, K_f = gain, T_{HPF} = time constant of (high-pass) frequency filter. Adapted from [52].*

The control block diagrams shown above represent the examples of the additional controls and signals that should be added to the initial converter controls if the wind turbine generator were about to be equipped with the inertia emulation function. In the control block diagrams shown in Figure 10, Figure 11 and Figure 12, the frequency signal is filtered in order to smooth the temporary frequency swings. In the case of synthetic inertia as well as power boost proportional to frequency derivative, the frequency signal is filtered by a first-order filter to remove the noise originating from the measurement and amplified by the derivation [52], as demonstrated in Figure 12.

The performance of fixed power boost in the Nordic power system is studied by the simulations presented in Chapter 6. In turn, the control method of synthetic inertia is analyzed according to the literature in Section 3.3. As mentioned above, the combinations of the control methods might also be beneficial. Thus, the combination of power boost proportional to frequency change and power boost proportional to frequency derivative is also studied in this thesis. To refer to this combination, the concept of proportional power boost is used in this thesis.

3.2.4 Present requirement criteria

In order to set suggestions for an inertia emulation requirement, the suitable controller parametrization must be validated according to reasonable simulations. The typical inertia emulation requirement criteria include

- activation frequency [Hz] or alternatively frequency dead band [Hz],
- power boost rise time [s] or alternatively the frequency for maximum power boost [Hz],
- power boost percentage [percentage of pre-disturbance power or percentage of rated power],
- power boost (phase) duration [s],
- power drop during the recovery phase [percentage of pre-disturbance power or percentage of rated power],
- recovery (phase) duration [s],
- minimum output power for availability [percentage of rated power],
- time between consecutive activations.

The list above is based on the inertia emulation requirements in force regarding Hydro-Québec's requirement presented in [2][39][40] and regarding IESO's requirement presented in [13][41][42][43]. This study however shows that some additional issues are recommended to be covered in the requirement if such requirement were introduced in the Nordic power system. These issues are discussed in Section 7.2.

Firstly, the *activation frequency* determines the system frequency at which the power boost of the inertia emulation functionality is activated. Instead of setting a frequency threshold, it is also possible to set a *frequency dead band* that denotes a frequency range in which the power boost of the inertia emulation functionality is not activated. The activation of power boost is typically limited either by an activation frequency or a frequency dead band since, according to the in force inertia emulation requirements, the inertia emulation is not designed to constantly control the frequency but support the system frequency during significant under-frequency events.

The *power boost rise time* is the time in seconds that it takes until the power boost has reached its maximum value after the activation frequency or frequency dead band is exceeded. Alternatively, the gradient of the power boost can also be controlled by setting the activation frequency and the frequency for maximum power boost as desired. The frequency for maximum power boost denotes the frequency at which the power boost reaches its maximum.

The *power boost* refers to the amount of the additional active power either as a percentage of the actual power output of each wind turbine generator in service before the incident or as a percentage of the rated power of each wind turbine generator in service. In turn, the *power boost duration* is the time in seconds that is takes from the beginning of the rise of the active power (activation of power boost) until the beginning of its descent (deactivation of power boost).

The recovery phase characteristics, namely the *power drop during the recovery phase* and *recovery duration*, are noticed to be critical for the suitability of inertia emulation functionality for a power system. To enable a smooth recovery and active power drop low enough, the recovery duration should be long enough. It may also be beneficial to set the recovery phases in different wind power plants to start gradually at different moments of time.

In addition to the parameters presented in the list above, it may be useful to set an activation delay for the inertia emulation functionality that is the time in seconds that can be utilized in order to avoid the undesired activation of inertia emulation due to a short-duration self-exiting frequency swing by delaying the power boost activation. This type of frequency swing could be caused by inter-area power oscillations that are typical in certain power flow situations in the Nordic power system. However, setting an activation delay should be considered and implemented with caution. A suitable filtering of the frequency signal is another solution to avoid undesired activation of inertia emulation due to a short-duration self-exiting frequency swing. Filtering low-frequency oscillations, such as the inter-area power oscillations in the Nordic power system, would however require some delay.

For the requirement design, *minimum output power for the availability* of the inertia emulation capability shall be considered as well. This issue is covered in Section 3.2.5.

3.2.5 Limitations

It is likely that there is a limit for the operating range in which the inertia emulation capability is available. Namely, at low wind speeds the rotational speed of the wind turbine rotor is already slow and slowing down the rotor even more may not be possible without unintentionally stopping its rotation. The data sheets of the turbine generators available for the author do not mention any this type of availability limits for inertia emulation. However, according to the doctoral thesis of Johan Björnstedt from Lund University, wind turbines from several manufacturers would be able to provide inertia emulation with power boost of 10% of the wind turbine generator rated power for 10 seconds for all wind speeds [3], in other words, at all the operating points of the power curve.

According to the manufacturers contacted by the author, this is true from the electrical side only [38][50]. Namely, there are some restrictions originating from the aerodynamic side. According to a manufacturer, the inertia emulation is not available below 25% of rated active power [50]. Additionally, such high and long power boost provided around rated wind speed could cause high active power reduction during the recovery phase [38]. Therefore, the inertia emulation functionality cannot be required at the lowest power outputs. For example, two Canadian TSOs (Hydro-Québec and IESO) require the inertia emulation availability from 25% of rated active power [2][13][39]. Thus, it is reasonable assumption that inertia emulation could be required at least above 25% of rated active power.

The converters of wind turbine generators can occasionally be overloaded for a short period of time which enables that the inertia emulation is available also at rated power (at and above the nominal wind speed) as the inertia emulation requirements typically stipulate. However, at high active power levels a wind power plant operates close to its apparent power maximum the converter cannot exceed. Either the provision of active or reactive power may therefore have to be limited as the wind turbine generator is operating above the rated power. Hence, the reactive power provision may have to be limited if the inertia emulation functionality is activated providing active power above 1.0pu.

Figure 13 presents a suggestive capability curve of a modern wind turbine generator. The lighter area in the figure emphasizes the possible restriction of the reactive power capability related to the exceeding of the rated power. Therefore, it should be determined whether it is the frequency support by the active power provision or the voltage support by the reactive power provision that should be prioritized as the wind turbine generator is operating above the rated power.

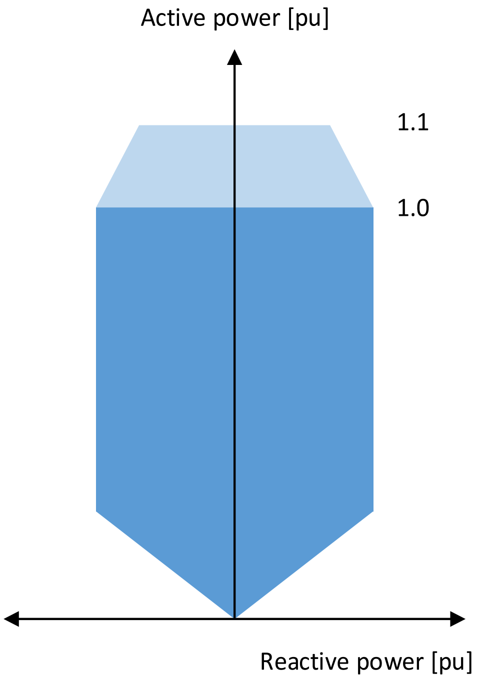

Figure 13. *Indicative capability curve of a modern wind turbine generator. The lighter area demonstrates the possible restriction of the reactive power capability related to the exceeding of the rated power. Adapted from [1] (p. 228).*

3.3 Performance of synthetic inertia

The concept of synthetic inertia denotes the inertia emulation functionality controlled in such a way that the power boost is proportional to the RoCoF (*df/dt*). Simulations with synthetic inertia are not performed in this thesis but the variant referred to as proportional power boost is analyzed by simulations instead (see Section 3.2.3 for description). However, in the doctoral thesis of Johan Björnstedt from Lund University, the performance of synthetic inertia on the frequency dynamics in the Nordic power system is studied [3]. Some of the most essential parts of the simulations presented in the doctoral thesis are summarized next.

Inter-area power oscillations appear in the Nordic power system. Therefore, the frequency signal utilized for the *df/dt* control of synthetic inertia contains low frequency oscillations in addition to the noise originating from the measurement [3]. Figure 14 highlights the challenges related to control of synthetic inertia in real systems with power oscillations. The frequency shown in the figure represents the event with the highest amplitude of frequency oscillation occurred in the Nordic power system in 2007–2010 [3]. The corresponding *df/dt* (without filtering) is also shown in the figure. As can be seen, remarkable oscillations and noise appear in the calculated *df/dt*. If the original frequency measurement would not be filtered, the oscillations and noise would be reflected in the power boost of inertia emulation, too. This would result in the bad performance of inertia emulation.

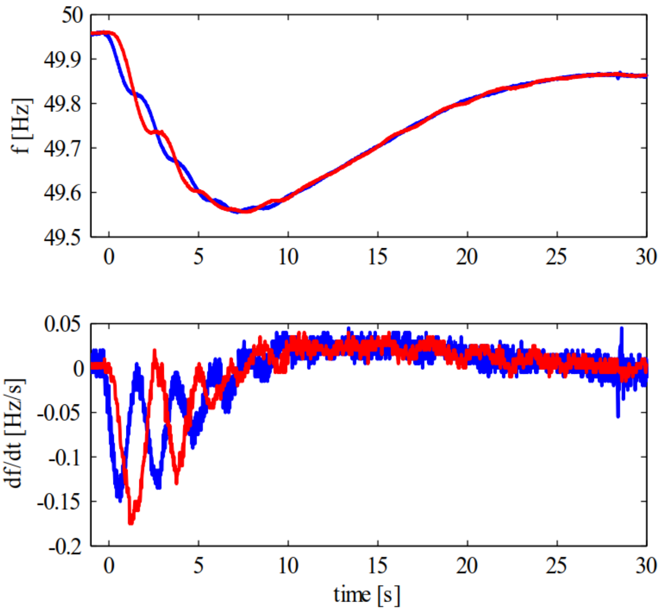

Figure 14. *Measured frequency and calculated df/dt in Southern Sweden (blue) and in Southern Finland (red) [3].*

Figure 15 shows the performance of synthetic inertia in low and high wind power penetration cases. The simulations are executed in PowerFactory and the system model utilized is a simplified two-area four-machine representation of the Nordic power system [3]. The frequency used calculating the *df/dt* is filtered with a 1 Hz low-pass filter in order to eliminate the noise and to enhance the performance of inertia emulation [3]. In the case of low wind power penetration, there appear undesired oscillations in the wind turbine generator output power and, thus, the performance of inertia emulation is inadequate [3]. In turn, in the case of high wind power penetration, the damping of oscillations is improved [3]. However, the performance of inertia emulation to improve the frequency nadir does not seem excellent either in this case. In conclusion, achieving a satisfactory performance of synthetic inertia or power boost proportional to frequency derivative requires that the frequency signal is reasonably filtered.

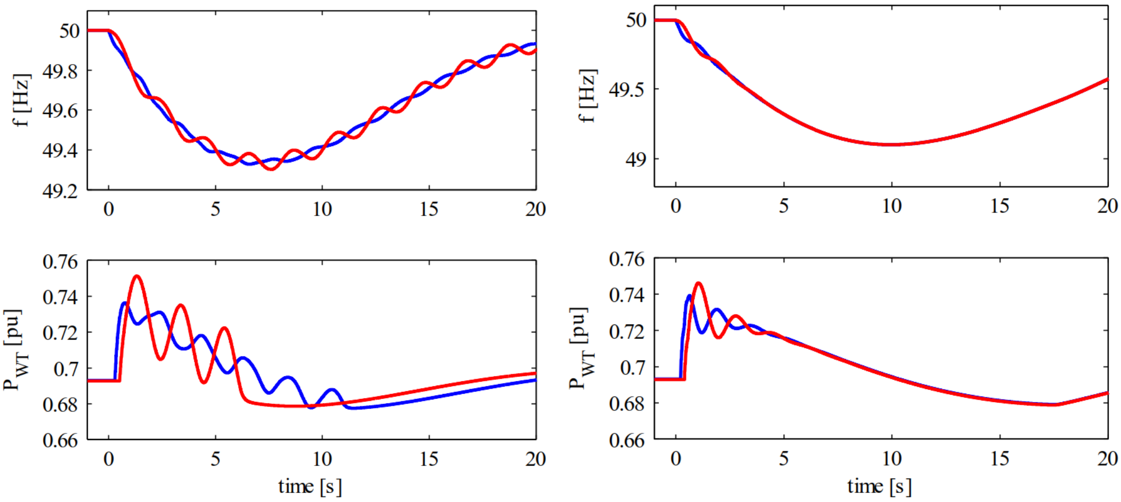

Figure 15. *Performance of synthetic inertia in low wind power penetration case (left) and high wind power penetration case (right). Frequency f at generators G2 (blue) and G3 (red) and wind turbine output power P_{WT} connected at buses 1 (blue) and 4 (red). Frequency used calculating the df/dt is filtered with a 1 Hz low-pass filter. Adapted from [3].*

In addition, Vattenfall Research and Development studied the possibilities of synthetic inertia in the Nordic power system with a simplified system model in PSS®E [57]. According to the study, the inertia emulation provided by the control method of synthetic inertia does not seem very useful in improving the frequency nadir [57].

By analyzing Figure 15, it can be observed that the major active power contribution is provided almost instantly after the beginning of the disturbance event. This observation most likely explains why the usage of synthetic inertia may result in the improvements in the RoCoF instead of the frequency nadir. Therefore, when aiming to primarily improve the frequency nadir, implementing the activation frequency or dead band may be useful when using the inertia emulation control method which power boost is proportional to the frequency derivative.

4. EXAMPLES ON MANAGING UNDER-FREQUENCY EVENTS IN POWER SYSTEMS WITH LOW INERTIA

In this chapter, inertia emulation of wind power plants and an ancillary service called fast frequency response are covered as examples on practices managing the RoCoF and frequency nadir during under-frequency events used in real systems with low inertia are described and compared. Additionally, the performance of inertia emulation in Hydro-Québec's system is briefly analyzed.

4.1 Practices utilized in Canada, Ireland and Northern Ireland

This section focuses on the practices to acquire additional active power support utilized in Canada, Ireland and Northern Ireland in order to manage the early stages of under-frequency events.

4.1.1 Acquiring additional active power support

As the wind power penetration has increased significantly, TSOs around the world have encountered the problem of decreasing power system inertia. To cope with this change, TSOs have studied the issue and tried to find suitable solutions, for example, to manage RoCoF and frequency nadir during the early stages of under-frequency events in their power systems.

Some TSOs, such as the Canadian TSOs Hydro-Québec and Independent Electricity System Operator (IESO), have set an inertia emulation requirement for converter-connected wind power plants connected in their networks. These inertia emulation requirements are studied in Section 4.1.2 and Section 4.1.3. The inertia emulation requirements are formulated using the requirement parameters described in Section 3.2.4.

Another option to acquire additional active power support could be complementing the ancillary services, also known as system support services or system services, with a so-called inertia market. The TSOs EirGrid in Ireland and System Operator Northern Ireland (SONI) in Northern Ireland, for example, will introduce an ancillary service market for generation and consumption able to provide active power contribution fast enough. This option is described in Section 4.1.4.

4.1.2 Hydro-Québec's inertia emulation requirement

For several years Hydro-Québec has required inertial response during large, short-duration frequency deviations from wind power plants with a rated power output exceeding 10 MW [40]. The initial version of the inertia emulation requirement was specified in 2009 [40] and entirely revised in 2012 [2][39]. The revised inertia emulation requirement is summarized in Table 5. As the table reveals, the power boost requirements are based on the rating of the plant rather than on the pre-disturbance power [2][39]. Additionally, it must be possible to adjust the dead band between −0.1 Hz and −1.0 Hz of the nominal frequency of the network [2][39]. An adjustable dead band enables individual adjustments of inertia emulation activation for separate wind power plants.

Table 5. *Hydro-Québec's inertia emulation requirement for WPPs [2][39].*

Inertia emulation requirement	
Objective	Used only during large, short-duration under-frequency events
Control method	Either fixed power boost or power boost proportional to frequency change
Frequency dead band	Adjustable dead band between the deviation of −0.1 Hz and −1.0 Hz from the nominal grid frequency of 60 Hz
Power boost rise time	≤ 1.5 s
Power boost percentage	≥ 6% of rated active power of each WTG in service
Power boost duration	≥ 9 s
Power drop during the recovery phase	≤ 20% of rated active power of each WTG in service
Availability of the functionality	≥ 25% of rated active power of each WTG in service
Time between consecutive activations	≥ 2 min after the end of the recovery phase

According to the latest grid code document, each installed wind power plant must pass the validation tests in order to prove the required operation [39]. In this connection it should be noted that the operation of the wind power plant prevails rather than the operation of the individual wind turbine generators [39].

4.1.3 IESO's inertia emulation requirement

An inertia emulation requirement of converter-connected wind power plants is also introduced by IESO, another Canadian system operator. According to the Market Rules Appendix 4.2 [42] and the specifying background document for Large Renewable Procurement I [41], IESO's requirement concerns converter-connected wind power plants with rated power exceeding 50 MW. Also the wind power plants in IESO's network must prove that the performance of the wind power plant meets the requirements [43]. The main features of IESO's inertial response requirement are collected into Table 6.

Table 6. *IESO's inertia emulation requirement for WPPs [13][41].*

Inertia emulation requirement	
Objective	To respond to under-frequency events by temporarily increasing the active power output
Control method	Not specified
Activation frequency	Deviation of −0.3 Hz from the nominal grid frequency of 60 Hz
Power boost rise time	≤ 0.5 s
Power boost percentage	≥ 10% of pre-disturbance active power
Power boost duration	≥ 10 s
Power drop during the recovery phase	≤ 5% of pre-disturbance active power
Availability of the functionality	≥ 25% of rated active power
Time between consecutive activations	Not specified

4.1.4 EirGrid and SONI's market for fast frequency response

In order to manage the decreasing system inertia due to the increasing share of non-synchronous generation, the Irish TSO EirGrid and the Northern Irish TSO SONI have proposed an alternative solution to manage low inertia in their power systems. Instead of stipulating inertia emulation capability from wind power plants, EirGrid and SONI will introduce an ancillary service market for fast frequency response (FFR) [5][6]. In addition to fast frequency response, EirGrid and SONI will introduce other new ancillary service products including synchronous inertial response (SIR) that is related to fast frequency response by the objective of managing frequency nadir [5].

In EirGrid and SONI's documentation, fast frequency response denotes the additional increase in active power output from a generator or reduction in active power demand during a frequency disturbance [5]. The fast frequency response is utilized to manage under-frequency events by increasing the time to reach frequency nadir and mitigating the RoCoF [5][7]. The idea of the fast frequency response is that both synchronous and asynchronous machines can emulate any inherent inertial response by reasonable controls [5].

The fast frequency response should be available within 2 seconds after the beginning of the frequency disturbance event and for at least 8 seconds after its activation [5]. This means that the fast frequency response should be available 3 seconds faster than the primary operating reserve [6]. By their objective, the primary operating reserve in EirGrid and SONI's systems is corresponding to the reserve product of frequency containment reserves in the Nordic power system. In the requirement of this new fast frequency response product, there is no specific limit for the active power drop during the recovery phase. However, the energy needed in the first 10 seconds of the recovery phase should not exceed the additional energy provided during the power contribution [5]. This is emphasized by the hatched areas in Figure 16 that shows an example of the operation of the fast frequency response product.

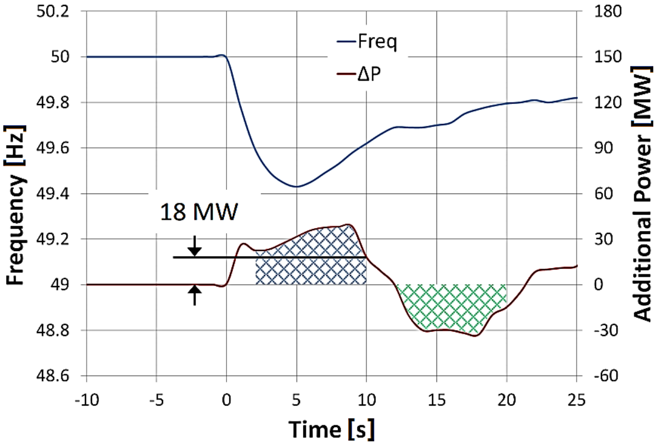

Figure 16. *Example of the operation of the fast frequency response product. Upper curve: frequency. Lower curve: additional power. The energy provided during the power contribution (hatched area on the left) must be greater than the energy needed in the 10 first seconds of the recovery phase (the hatched area on the right). Adapted from [5].*

In April 2016, EirGrid and SONI published the proposed tariff payment rates used during the 2016–2017 tariff years representing the interim period of the implementation project of the new ancillary services [6]. In the consultation paper, the interim tariff rate of 1.96 €/MWh was proposed for the fast frequency response [6]. Moreover, the tariff payment rates proposed for the interim period will be questioned and updated for the enduring arrangements [6].

4.1.5 Comparison of the practices

Since every power system is unique and, therefore, has specific needs for the frequency response, the inertial response requirements vary between the TSOs, as emphasized in [13]. For example, the requirement set by Hydro-Québec and IESO aim to improve especially the frequency nadir [13], whereas EirGrid and SONI are mainly trying to improve the RoCoF values [6][7].

Table 7 presents the inertia emulation requirements of Hydro-Quebec and IESO as well as the common fast frequency response requirement approved in the networks of EirGrid and SONI. According to the table, the upper limit for rise time varies between 0.5–2.0 s and the minimum acceptable power boost duration varies normally between 8–10 s. Hydro-Québec requires an adjustable frequency dead band for power boost activation. In turn, IESO has determined a specific threshold for the frequency at which the power boost is required to become active. Additionally, IESO's active power boost requirements are based on the actual pre-disturbance power output of the wind turbine generator, whereas

Hydro-Québec's corresponding requirements are based on the rated power. Though the recovery phase characteristics are critical for the power system operation, none of the TSOs studied requires a specific recovery duration, for example. Neither Hydro-Quebec nor IESO however allow active power to decrease arbitrarily as the recovery phase characteristics are determined by the active power drop limit.

EirGrid and SONI do not have any specific requirements on active power contribution or reduction during the recovery phase but it is stated in the documentation that the energy provided during the active power contribution has to be higher than the energy needed during the first 10 seconds of the recovery phase [5]. This is emphasized by the star symbol in Table 7.

Table 7. *Comparison of the additional active power support options.*

Criterion	**Hydro-Québec** [2][39]	**IESO** [13][41]	**EirGrid & SONI** [5]
Function	Inertia emulation from converter-connected WPPs	Inertia emulation from converter-connected WPPs	Fast frequency response
Activation frequency / Frequency dead band	[−0.1, −1.0] Hz, adjustable	−0.3 Hz	Not specified
Power boost rise time	≤ 1.5 s	≤ 0.5 s	≤ 2 s
Power boost percentage	≥ 6% of rated active power	≥ 10% of pre-disturbance active power	Not specified*
Power boost duration	≥ 9 s	≥ 10 s	≥ 8 s
Power drop during the recovery phase	≤ 20% of rated active power	≤ 5% of pre-disturbance active power	Not specified*
Availability of the functionality	≥ 25% of rated power	≥ 25% of rated power	Not specified
Time between consecutive activations	≥ 2 min after the end of the recovery phase	Not specified	Not specified
*the energy provided during the power contribution should always higher than the energy needed during the first 10 s of the recovery phase			

4.2 Inertia emulation performance in Hydro-Québec's system

In Hydro-Québec's system, the inertia emulation requirement has already been in force for several years. Next the performance of inertia emulation during an under-frequency event in Hydro-Québec's system is studied according to the analysis presented in [2].

On 28 December 2015, a sudden loss of a 753/315 kV transformer between a generation center and the main grid caused a disconnection of 1700 MW net generation [2]. The nominal frequency of Hydro-Québec's system is 60 Hz and the threshold for under-frequency load shedding is 58.50 Hz [2]. The event caused a frequency nadir of 59.08 Hz [2].

When the event occurred, 1209 MW of wind power generation were equipped with inertia emulation function, whereas the remaining 851 MW of wind power generation was not [2]. At that time, the wind power plants equipped with an inertia emulation function in Hydro-Québec's system were manufactured by Senvion (Type 3 WTGs) and Enercon (Type 4 WTGs) [2]. The Senvion wind power plants provided inertia emulation by control method of fixed power boost with activation frequency of 59.5 Hz [2]. In turn, the Enercon wind power plants utilized power boost proportional to the frequency change with activation frequency of 59.7 Hz [2].

Figure 17 shows the system frequency response and the power variation as a percentage of rated power from different types of wind power plants during the under-frequency event. During the power boost phase, the inertia emulation functionality behaved well since the wind power plants provided additional active power as designed, and consequently, the frequency nadir was improved [2]. However, there occurred a secondary frequency nadir in the system frequency during the recovery phase of the inertia emulating wind power plants [2]. The reason for the secondary frequency nadir is justified by the analysis based on the measurement data and the calculated RoCoF presented in Figure 18. As Figure 18 proves, the power of the inertia emulating wind power plants reaches its minimum value exactly at the same time with the second RoCoF minimum peak [2]. Therefore, it can be stated that the secondary frequency nadir was caused by the aggressive active power drop during the first 5 seconds of the recovery phase [2] also shown in Figure 17.

As can be seen from Figure 17, the recovery characteristics between the Senvion wind power plants and the Enercon wind power plants differ significantly from each other [2]. The recovery phase of the Senvion wind power plants is lengthened to 40–60s, whereas the recovery phase of the Enercon wind power plants lasts only 20–30s and the rotational speed of the wind turbine generator is restored rapidly to the optimum value. The greatest instantaneous power drop of Enercon wind power plants during the recovery phase was 12% (−144 MW), whereas the corresponding value for Senvion wind power plants was 3% (−32 MW) [2].

Both the Senvion and the Enercon wind power plants fulfill the Hydro-Québec's inertia emulation requirement [2]. However, a smoother recovery characteristics stretched over a longer period of time with a slighter power drop is more desirable than a steeper power drop caused by a fast restoration of the rotational speed [2]. This preference is due to the risk of delaying the frequency recovery and causing a secondary frequency nadir [2].

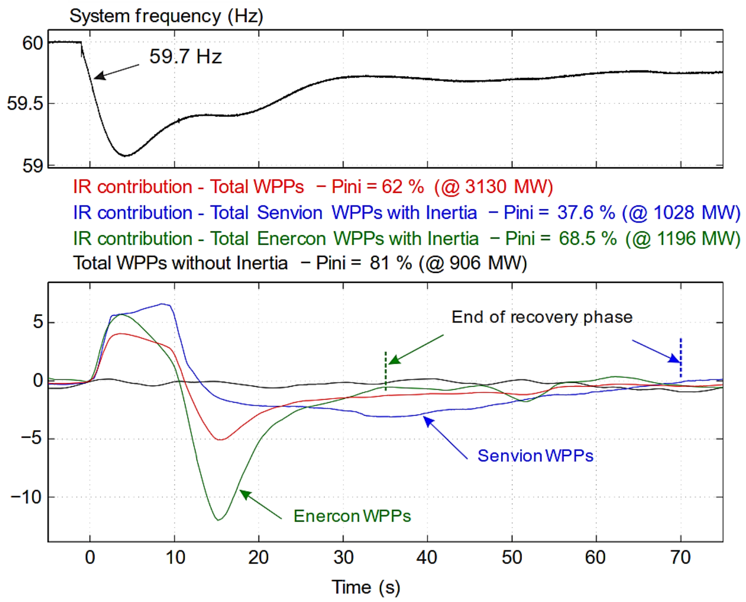

Figure 17. *System frequency response and power variation (% of rated power) from different types of WPPs during the under-frequency event. Lower graph: total WPPs (red), Senvion WPPs (blue), Enercon WPPs (green), and WPPs without inertia emulation (black). IR = inertial response. [2]*

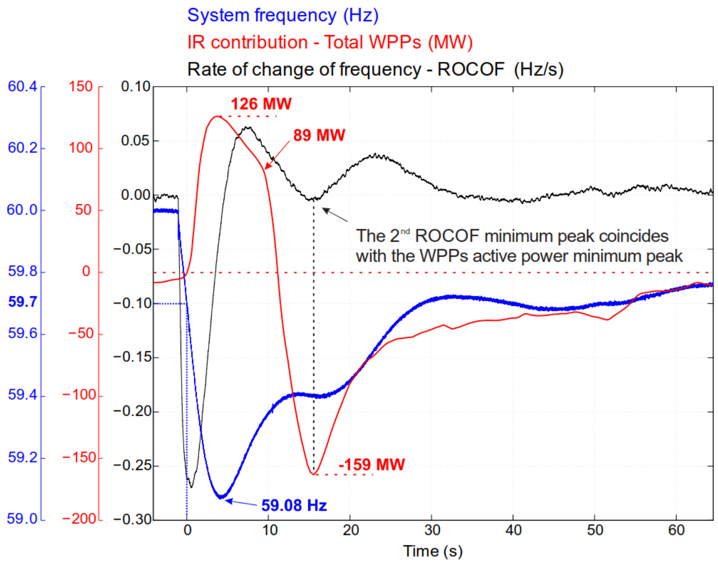

Figure 18. *Inertial response contribution. IR = inertial response. [2]*

The simulations in Figure 19 demonstrate a problem that may arise if the secondary nadir caused by the power drop during the recovery phase occurs undesirably. To be precise, the inertia emulation can help to retain a margin from the under-frequency load shedding threshold of 58.5 Hz but the recovery characteristics may jeopardize the 59 Hz / 15 s UFLS criterion according to which the under-frequency load shedding is activated if the frequency remains below 59 Hz for 15 seconds, as highlighted in the figure.

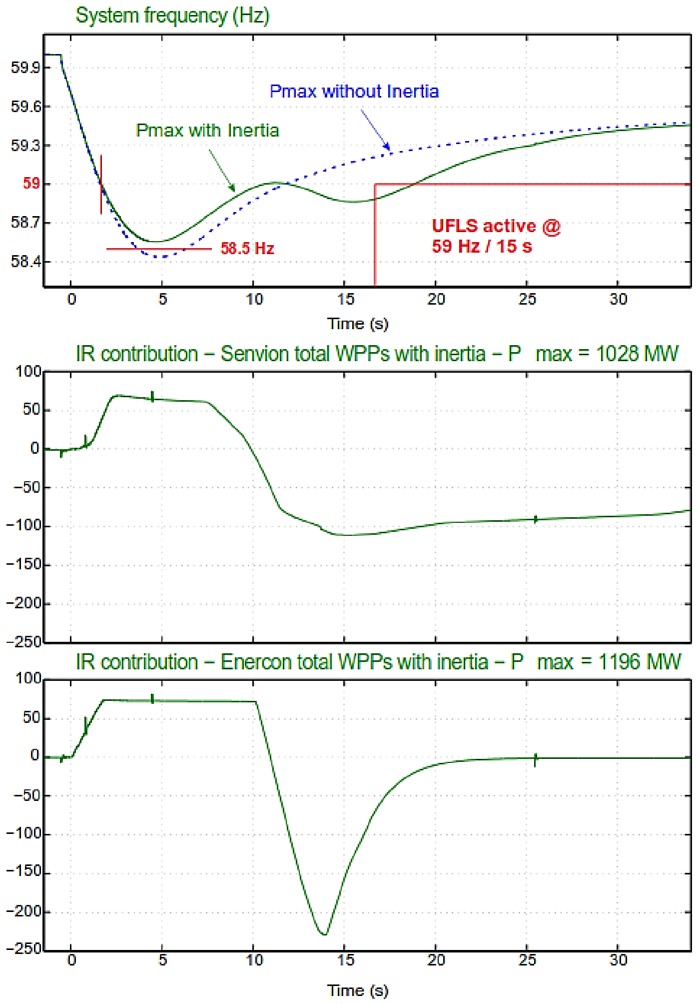

Figure 19. *Simulated impact of inertia emulation on system frequency in a scenario with maximum wind power and low inertia. IR = inertial response. [2]*

These observations emphasize that especially the recovery characteristics of inertia emulation need to be properly required by the TSO if such function is required. If inertia emulation was decided to be required in the Nordic power system, the function should operate appropriately if it met the requirement. Therefore, the possible inertia emulation requirement in the Nordic power system should be detailed enough. Thus, the inertia emulation requirement would not accept a significant power reduction during the recovery phase, for example. The suggestions for inertia emulation requirement setting are listed in Section 7.2.

5. MODELS AND SIMULATION SETUP

This chapter presents the implementation of the frequency disturbance simulations. The wind turbine generator models used in the simulations are briefly described as well.

5.1 Implementation of the simulations

The impact of inertia emulation capability of converter-connected wind power plants in the Nordic power system is analyzed by simulating the operation of the system in different power flow situations during different frequency disturbance events. Thus, this section covers the descriptions of the power system model as well as the selected power flow cases and disturbance events.

5.1.1 Power system model and calculation software

The simulations are carried out in the Nordic power system model in PSS®E Version 33. The calculation software is used widely all over the world for simulating the power system power flows and dynamics. Hence, the software is proven in use. The power system model utilized in this thesis is built for planning projects that concern a system-wide phenomenon, such as frequency stability. The model is built in cooperation with the Nordic TSOs and the earlier versions of it have been in use for years. The reliability of the system model is therefore verified to perform well for this type of examinations.

The Nordic power system model represents the synchronously operating Nordic system consisting of the power grids of Finland, Sweden, Norway and Denmark as well as the interconnections to the power grids in Russia, the Baltic countries, Poland and Germany. The major parts of the components, such as all the generators with rated power of 10 MW or higher, in the Nordic power system and their dynamics are modeled in the system model. Therefore, the system model can be considered detailed and the impact of the inter-area power oscillations on the performance of inertia emulation can be studied, for example. Additionally, the utilization of a detailed manufacturer-specific model of a wind power plant (described in Section 5.2) in a detailed power system model may reveal some possible restrictions that would not be revealed with simplified models. Though only one manufacturer-specific wind power plant model is used, merely the observations that can be generalized are used when drawing conclusions suggestions for requirement setting. The principle of the analysis is to use the manufacturer-specific model to demonstrate the issues that must be covered in the requirement or otherwise the system stability can be compromised.

The power system model is based on the future scenario formed to represent the Nordic power system in 2025 since the low inertia related problems during frequency disturbances will be more actual then. As described in Section 2.1, the Nordic power system will encounter some substantial changes in its power generation during the following years until 2025. In order to prepare for the future needs, the transmission capacity between Sweden and Finland will be increased due to the commissioning of the third AC interconnector between Sweden and Finland. In addition, the internal transmission capacity between Northern and Southern Finland will also be significantly increased.

5.1.2 Power flow cases

In this thesis, the inertia emulation functionality is studied in five power flow cases. The power flow cases differ from each other by the level and direction of AC transmission from Sweden to Finland, the level of system inertia, and the level of consumption as well as the wind power capacity. The AC transmission from Sweden to Finland, system inertia, and consumption determine which stability criterion is emphasized. By this kind of division, it is possible to study the effect of inertia emulation on each stability criteria, namely frequency stability, voltage stability, and damping of inter-area power oscillations separately, as well as on the overall stability of the system. Therefore, the power flow cases can be divided in three groups by the phenomenon emphasized relative to the three stability criteria. The power flow cases are listed in Table 8.

Table 8. *Power flow cases and their key characteristics.*

Power flow case	**Wind power capacity equipped with inertia emulation [MW]**	**AC transmission from Sweden to Finland [MW]**	**Inertia [GWs]**	**Load [MW]**	**Generation [MW]**	**Phenomenon emphasized**
Summer night case with low import IE1000	1000 (operating at rated power)	1050	125	23 640 (minimum)	24 270	Frequency stability
Summer night case with low import IE2000	2000 (operating at rated power)	1050	122	23 640 (minimum)	24 310	Frequency stability
Summer night case with low import IE4000	4000 (operating at rated power)	1050	121	23 640 (minimum)	24 460	Frequency stability
Winter case with maximum import	4000 (operating at rated power)	2100	258	57 100 (maximum)	59 060	Voltage stability
Summer night case with maximum export	4000 (operating at rated power)	−2100	129	23 640 (minimum)	24 590	Damping of power oscillations

In order to study the performance of inertia emulation and to determine the capacity of inertia emulating converter-connected wind power generation needed to improve the frequency stability of the Nordic power system, several additional wind power plants must be inserted in the power system model. The converter-connected wind power plants equipped with inertia emulation function are inserted in the power system model at eight substations A–H that locates in Finland. As the inertia emulating wind power capacity would entirely locate in Finland. The substations, at which the additional wind power plants are connected in the simulation model, locate geographically in East Bothnia and Sea Lapland where the wind power generation in Finland is mainly expected to locate in 2025 as shown in Figure 20. The substations are Keminmaa (A), Simojoki (B), Isokangas (C), Pikkarala (D), Siikajoki (E), Jylkkä (F), Ventusneva (G), and Pirttikylä (H).

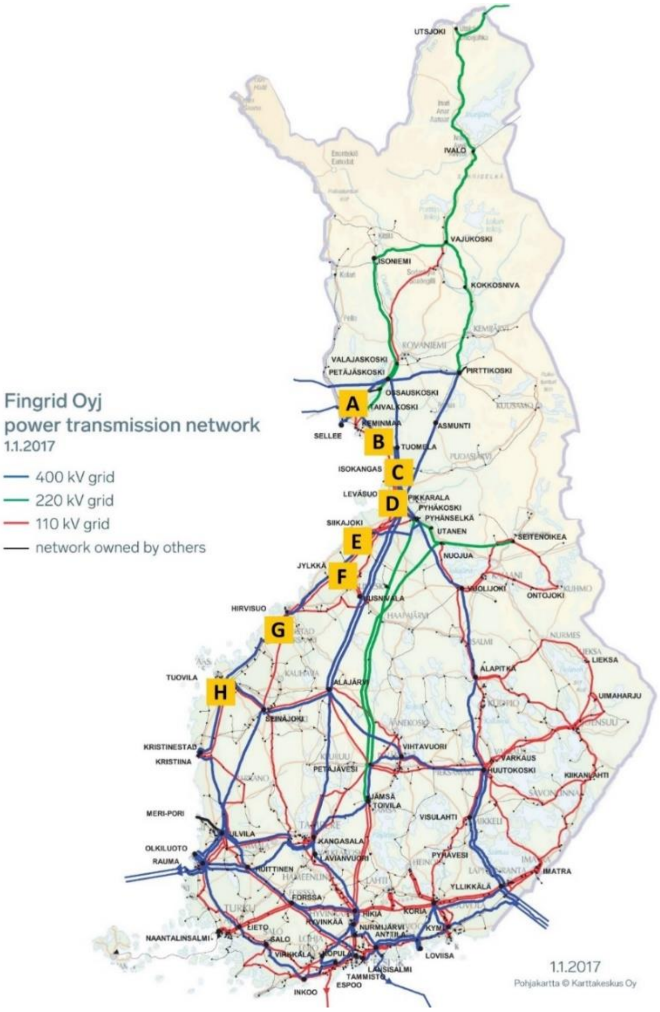

Figure 20. *Substations at which the wind power plants equipped with inertia emulation are connected in the simulation model and their approximate geographical locations (boxes with a letter identification). Adapted from [29].*

The investigation mainly focuses on the summer night cases with low import and especially on the case with 4000 MW wind power capacity equipped with inertia emulation operating at full power. With this case it is possible to study the performance of inertia emulation on frequency stability that is the primary objective of this thesis. The effect of inertia emulation on voltage stability can be analyzed by the winter case with maximum import in which both the consumption and the AC transmission from Sweden to Finland are at maximum. In turn, the summer night case with maximum export enables the analysis of the effect of inertia emulation on the damping of power oscillations. The wind power capacity mentioned in the table does not give the total wind power capacity, as one might suppose at first, rather it gives the capacity of inertia emulating converter-connected wind power exclusively.

The capacity of wind power capacity equipped with inertia emulation is varied in the simulation cases to estimate the amount of inertia emulating generation needed so that the inertia emulation would impact on the frequency stability in comparison to the benchmark when the inertia emulation function is off.

5.1.3 Disturbance events

As explained above, the inertial response from converter-connected wind power plants is examined by simulating the power system while being subjected to a frequency disturbance causing an under-frequency event. When studying the performance and effects of the inertia emulation function, the most important time frame takes place 0–40 s after the beginning of the frequency disturbance event. During this time frame, the inertia emulation activates only a few seconds after the disturbance, which is before the frequency containment reserves have activated, and eventually, the recovery phase has ended or at least the most critical part of the recovery phase is over approximately at 40 s after the beginning of the frequency disturbance event. Namely, the most significant power reduction during the recovery phase occurs during the first 5–20 s after the end of the power boost phase. Therefore, the total simulation time of 60 s is considered reasonable and selected in this study. Additionally, the disturbance occurs at 5 s. The frequency containment reserves are replaced with the automatic frequency restoration reserves minutes after the beginning of the frequency disturbance event. This effect is however considered unnecessary in this study. The analysis on the impact of inertia emulation on the reserves is however recommended for the future work.

The wind speed can be assumed constant during the power boost phase of inertia emulation since the duration of the power boost phase is in the order of 10 s. The assumption of constant wind speed is more inaccurate during the recovery phase. However, the power system is studied as a whole so the possible error is considered low.

In order to analyze the effects of inertia emulation, the inertia emulation simulations are compared with the benchmarks in which the inertia emulation functionality is off at each wind power plant equipped with the functionality. Examples of the benchmark simulations are shown in Figure 21, Figure 22, Figure 23, and Figure 24. The disturbance events studied are collected in Table 9.

Table 9. *Disturbance events.*

Disturbance event	Contingency	Power flow case
Disconnection of Olkiluoto 3 nuclear unit (at 1300 MW) as a result of a three-phase short circuit at the high voltage side of the main transformer	N−1	Summer night cases with low import, winter case with maximum import, summer night case with maximum export
Disconnection of Olkiluoto 3 nuclear unit (at 1300 MW) without a fault	N−1	Summer night case with low import IE4000, winter case with maximum import, summer night case with maximum export
Disconnection of Oskarshamn 3 nuclear unit (at full power of 1400 MW) as a result of a three-phase short circuit at the high voltage side of the main transformer	N−1	Summer night case with low import IE4000
Disconnections of Forsmark 3 nuclear unit (at full power of 1200 MW) and Fenno-Skan 2 HVDC link (800 MW) as a result of three-phase short circuit at a nearby bus bar	N−2	Summer night case with maximum export

The disconnection of Olkiluoto 3 nuclear unit located in Southern Finland represents the disconnection of the biggest generating unit in Finland in 2025 with the capacity of 1650 MW. The disconnection of Olkiluoto 3 at full power would therefore lead to a generation loss of 1650 MW. Thus, in a real system, a system protection scheme will be utilized to disconnect 350 MW load in Finland if Olkiluoto 3 at full power trips from the network. The idea is to limit the active power deficit to 1300 MW so that the dimensioning fault of the Nordic power system would not be increased. In order to study the event without the need for modeling the disconnection of the loads participating in the system protection scheme, the power output of Olkiluoto 3 in the simulations is therefore set at 1300 MW. The effect of the delays of the disconnecting loads participating the system protection scheme is not taken into account since the effect can be considered unimportant relative to this study in which the principal aim of the inertia emulation is to improve the frequency nadir occurring some seconds after the beginning after the fault. The disturbance event in which the disconnection is a result of a three-phase short circuit represents the worst case of the fault types, and thus, the frequency nadir is at the lowest.

The frequency responses without the effect of inertia emulation in different power flow cases when the Olkiluoto 3 disconnects as a result of a three-phase short circuit and when Olkiluoto 3 disconnects without a fault are shown in Figure 21. In turn, the disconnection of Oskarshamn 3, the biggest generating unit in Sweden, causes a generation loss of 1400 MW. As expected, the frequency responses of the disconnections of Olkiluoto 3 and

Oskarhamn 3 as a result of the three-phase short circuit are quite similar when the events are produced in the same power flow case. The frequency responses of the disconnection of Oskarshamn 3 are presented in Figure 23.

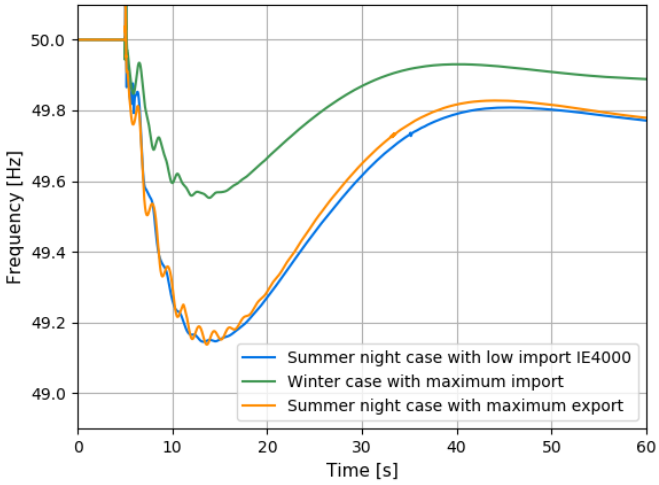

Figure 21. *Frequency responses (at Alapitkä substation in Finland) of the disconnection of Olkiluoto 3 as a result of a three-phase short circuit.*

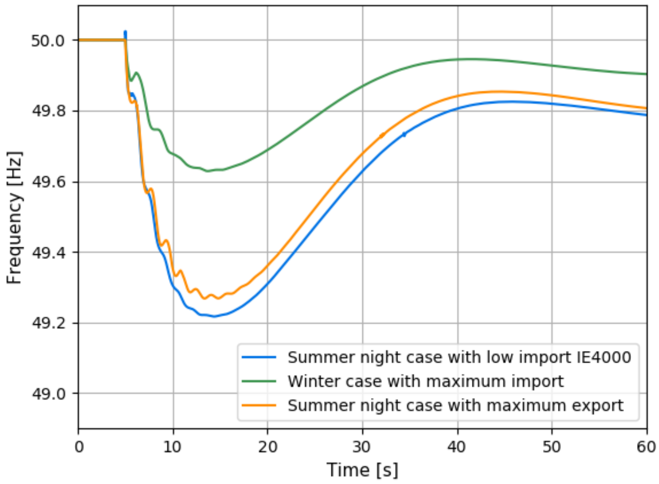

Figure 22. *Frequency responses (at Alapitkä substation in Finland) of the disconnection of Olkiluoto 3 without a fault.*

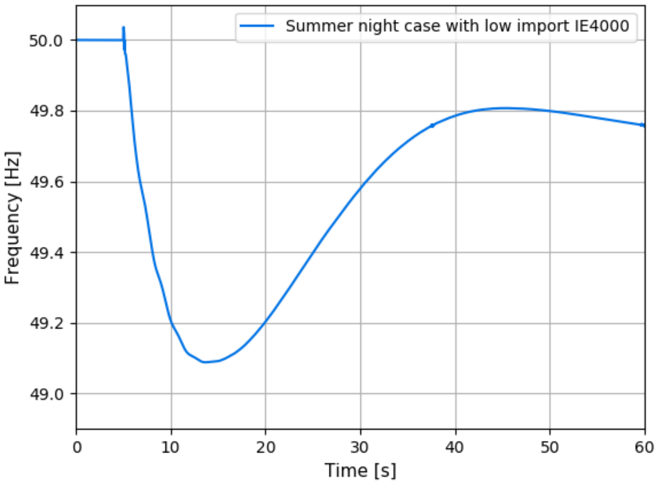

Figure 23. *Frequency responses (at Alapitkä substation in Finland) of disconnection of Oskarshamn 3 as a result of a three-phase short circuit.*

A combination of the disconnections of Forsmark 3 nuclear unit and Fenno-Skan 2 HVDC link as a result of a three-phase short circuit at a nearby bus bar in summer night case with maximum export causes a significant under-frequency event combined with large inter-area power oscillations as shown in Figure 24. This disturbance event represents N−2 contingency which means the disturbance does not include in the N−1 criteria described in Section 2.1. Additionally, this disturbance is not considered likely but it is interesting because of its severity and the inter-area oscillations.

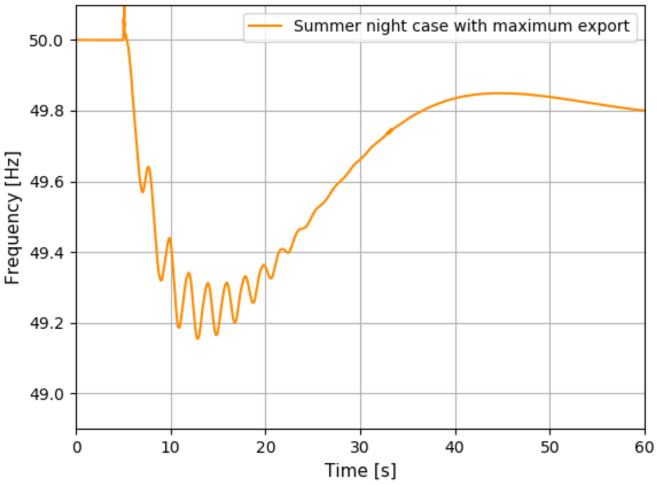

Figure 24. *Frequency responses (at Alapitkä substation in Finland) of disconnections of Forsmark 3 and Fenno-Skan 2 as a result of a three-phase short circuit.*

5.2 Wind power plant model

As manufacturer-specific dynamic wind power plant model for PSS®E is used in the simulations. This section summarizes the main features of the model.

5.2.1 Wind power plant model of Enercon

The wind power plant model of Enercon is utilized in the simulations presented in this thesis. The model represents Type 4 wind turbine generator technology. The dynamic model of Enercon wind power plant is divided in two parts: a model representing the aggregated wind turbine generators in the wind power plant and a model representing the control unit of the wind power plant. The dynamic data are provided correspondingly in two compiled object files (obj-files). This means that each wind power plant in the system is modeled by scaling a single wind turbine generator model and the scaled group of identical wind turbine generators is controlled by the wind farm control unit. In practice, this does not have impact on the results relative to the phenomenon studied since the errors of using an aggregated wind power plant model in system studies are minor [56].

The inertia emulation function of the Enercon wind turbine generator model has three modes: 1) off, 2) Constant power increase, and 3) Variable power increase [11]. The function can be adjusted by varying the following parameters (see Section 3.2.4 for the descriptions of requirement criteria):

- activation frequency [Hz],
- frequency for maximum power boost [Hz],
- deactivation frequency [Hz],
- power boost percentage [% of rated power],
- power boost for fixed duration of 0.3 s [% of rated power],
- power boost (phase) duration [s],
- recovery (phase) duration [s] [11].

According to the simulations executed by the author, the parameter of power boost for fixed duration of 0.3 s is not relevant if the parameters of power boost and boost duration are specified. Moreover, the power boost of duration of 0.3 s could probably be used to enhance the RoCoF but at least not the frequency nadir in the Nordic power system. Therefore, its effect is not analyzed in Section 6.1. The idea of the deactivation frequency is that the power boost deactivates and the function proceeds to the recovery phase if the system frequency exceeds the deactivation frequency before the power boost duration is over.

The inertia emulation control system of Enercon wind turbine generator model is presented Figure 25 for the inertia emulation mode of Constant power increase. The inertia emulation function activates when the frequency measurement crosses the activation frequency. When the mode of Constant power increase is used, the amount of power boost P_{boost} during power boost phase is determined as follows

$$P_{\text{boost}}(t) = \frac{f_{\text{activation}} - f(t)}{f_{\text{activation}} - f_{\text{max\_boost}}} P_{\text{boost\_percentage}} \, P_{\text{rated}} \tag{7}$$

where $f_{\text{activation}}$ is the activation frequency, $f(t)$ is the frequency measurement, $f_{\text{max\_boost}}$ is the frequency for maximum power boost, $P_{\text{boost\_percentage}}$ is the power boost percentage, and P_{rated} is the rated power of the wind turbine generator [10][36]. This means that, if the mode of Constant power increase is used, the power boost is linearly proportional to the absolute frequency change until the frequency for maximum power boost is reached. Since then, the power boost is fixed during the power boost phase which duration is defined by to the parameter of power boost duration. When the frequency for maximum power boost is reached, the function delivers the power boost as it is determined by the power boost percentage and the rated power of the wind turbine generator. Thus, the power output during the power boost phase after reaching the frequency for maximum power boost is the sum of the power boost and the power output at the moment when the inertia emulation function is activated. If the frequency for maximum power boost is not reached, the power boost is proportional to the absolute frequency change for the entire power boost phase.

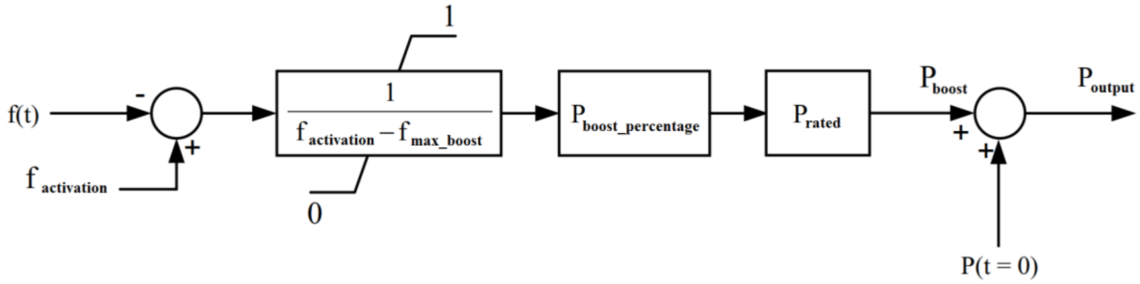

Figure 25. *Inertia emulation control system of Enercon WTG during the power boost phase of Constant power increase. f(t) = frequency measurement,* $f_{activation}$ *= activation frequency,* f_{max_boost} *= frequency for maximum power boost,* $P_{boost\_percentage}$ *= power boost percentage,* P_{rated} *= rated power,* P_{boost} *= power boost,* P_{output} *= WTG power output,* $P_{(t=0)}$ *= WTG power output at the moment when the inertia emulation function is activated. Adapted from [13].*

The behavior of the Constant power increase means that the inertia emulation mode is the combination of the control methods of fixed power boost and power boost proportional to frequency change (see Section 3.2.3 for the descriptions of control methods). In this thesis, value for the frequency for maximum power boost is set so that the grid frequency falls below it whenever any of the disturbance events studied is provided. By this selection, the performance of fixed power boost in the Nordic power system can be evaluated though the mode does not purely correspond the control method of fixed power boost.

The performance of power boost proportional to frequency change is thus not covered in this thesis.

If the mode of Variable power increase is used, the power boost is provided by the combination of the control methods of power boost proportional to frequency change and power boost proportional to frequency derivative. As described in Section 3.2.3, the concept of proportional power boost is used in this thesis to refer to this type of a combination. Thus, the duration of the power boost provision (power boost phase) cannot be controlled by a pre-defined the parameter of power boost duration since the power boost ends as the frequency starts to recover.

Thus, with this wind power plant model it would be possible to analyze the inertia emulation performance by control methods of fixed power boost, power boost proportional to frequency change and the combination of power boost proportional to frequency change and power boost proportional to frequency derivative (called proportional power boost in this thesis). However, only the control methods of fixed power boost and proportional power boost are studied in this thesis. Studying the control method of power boost proportional to frequency change is however recommended for the future work.

The wind power plant model of Enercon naturally has some limitations as models always have. For example, with the wind power plant model of Enercon, the power boost percentage can only be set with rated active power as a reference. However, this does not restrict the investigation in this thesis since the wind power plants equipped with inertia emulation operate at rated power. This makes it useless to study the inertia emulation function with actual active power as a base for the power boost percentage since the actual power used as a base would be equal to the rated power.

5.2.2 Validation of the wind power plant model

The dynamic model of the commercial wind power plants in the system model is parametrized to follow Fingrid's grid code for generators up to a certain point. Fingrid's grid code for generators applicable to the frequency response of wind power plants is summarized in Section 3.1. The dynamic models of commercial wind power plant used is validated by comparing the simulations with the simulations with a generic wind power plant model provided by the Western Electricity Coordinating Council (WECC) that is the basic model in PSS®E for wind power plant modeling and typically used in the Nordic power system model. The wind power plant manufacturer has validated the performance of their dynamic wind power plant model with field test measurements as shown in the technical reports of the models [9][11]. Unfortunately, the technical reports are only available for users under a non-disclosure agreement.

With the wind power plant model of the Enercon some differences were observed mainly in the reactive power and voltage support behavior. However, this is not considered a problem as the frequency response and active power behavior are prioritized in this thesis. It was also noticed that the active power of the wind power plant increases slightly after the disturbance and before settling at a new value after a couple of low amplitude oscillations when the frequency exceeds the value of 49.73 Hz approximately 30 s after the beginning of the disturbance event. This behavior occurs also when the inertia emulation function is on. The behavior is not documented in the technical report of the model and it cannot be analyzed by the user since the model is a so-called black-box model with some hidden parts. However, the unknown increase in the active power is slight and therefore considered insignificant relative to this study.

6. RESULTS OF THE SIMULATIONS

This chapter presents the main results of the frequency disturbance simulations. First, the performance of the inertia emulation function is investigated relative to frequency stability. Then, the effects of the function are assessed on the voltage stability as well as on the damping of power oscillations. Finally, the possible contradictions of the inertia emulation function and fault ride through function are studied.

6.1 Impact of inertia emulation on frequency stability

In this section, the impact of the control method and the parametrization on inertia emulation performance is studied from the frequency stability perspective. The simulations are executed using the summer night case with low import and the inertia emulating wind power capacity is 4000 MW unless otherwise specified. The manufacturer-specific wind power plant model used in the simulations is described in Section 5.2.1.

The frequency signal used in the control of the inertia emulation function is measured locally at the point of common coupling of each wind power plant. Therefore, the frequencies shown in the figures represent the frequency at the point of common coupling.

6.1.1 Studying the performance of inertia emulation

The following issues are taken into account when the performance of inertia emulation is studied:

- the improvement in the frequency nadir in comparison with the benchmark,
- the avoidance of a secondary nadir,
- the recovery of the frequency (the steady state frequency and the time that it takes until the steady state frequency is reached),
- the improvement in the RoCoF in comparison with the benchmark.

The issues in the list are not set in the order of importance but the issues are simultaneously considered as a part of the general view. However, it would be straightforward to set a minimum requirement for both the avoidance of a secondary and the recovery of the frequency.

In the Nordic power system, the inertia emulation is primarily desired to enhance the frequency nadir in comparison with the benchmark and, therefore, the improvements in the RoCoF are not at the highest priority. For power system security, it is crucial that the inertia emulation does not cause a secondary frequency nadir during the recovery phase. If the inertia emulation function was decided to be required in the Nordic power system, the requirement should be formulated detailed enough so that the recovery characteristics of the function would be smooth enough and thus the recovery phase would not contradict the under-frequency load shedding as the simulations in Hydro-Québec's system demonstrated in Section 4.2, for example. It is not desired either to arbitrarily delay the frequency recovery. However, slower frequency recovery could, for example, be managed by tightening the reserve activation requirements and therefore moderate delay in the frequency recovery is not considered a hindrance for inertia emulation in this thesis. It however must be analyzed separately which option would be the best solution for the power system as a whole and the effect of inertia emulation function on the reserves is recommended for the future work.

6.1.2 Performance of fixed power boost

The performance of inertia emulation generated by the control method of fixed power boost is studied in this section. The control method of fixed power boost is explained in Section 3.2.3 whereas the manufacturer-specific implementation of the control method of fixed power boost is described in Section 5.2.1.

The performance of inertia emulation depends greatly on the parametrization in addition to the control method and the implementation of the function. The parameters studied are the activation frequency, frequency for maximum power boost, power boost percentage, power boost duration, and recovery duration. The parameters used when studying their effect on the performance of the function are listed in Table 10.

The parameter settings shown in Table 10 are collected as follows. First, a large number of simulations were run in order to be able to study the effect and sensitivity of each parameter. The parameter setting yielding the best performance achieved with the wind power plant model studied was selected as a base for the parameter-specific analysis. The idea behind this choice was that once the other parameters that are not studied are set relatively reasonably, it is possible to reveal the effect of the parameter under the scope by varying its value. The most interesting or relevant ones of the simulations were selected to be presented in this thesis report.

There are several inertia emulating wind power plants connected at the eight substations as described in Section 5.1.2. The simulations shown in this section represent the simulations at the point of common coupling at one of the wind power plants connected at Pirttikylä substation unless otherwise specified. The wind power plant connected at Pirttikylä substation was selected since it is the southernmost substation of the eight substations studied, and thus, closest to Olkiluoto 3 nuclear unit. Additionally, the spikes in active power and frequency observed at 5 s in the figures presenting the simulations of the disconnection of Olkiluoto 3 as a result of three-phase short circuit are caused by the fault occurring at 5 s.

Table 10. *Inertia emulation parameters used when studying the effect of the parameters on the performance of the fixed power boost control. P_r = rated power.*

The effect of activation frequency	
Activation frequency	Either 49.40, 49.60, or 49.80 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of P_r
Power boost duration	5 s
Recovery duration	20 s
The effect of frequency for maximum power boost	
Activation frequency	49.60 Hz
Frequency for maximum power boost	Either 49.25, 49.40, or 49.55 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of P_r
Power boost duration	5 s
Recovery duration	20 s
The effect of power boost percentage	
Activation frequency	49.40 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	Either 1%, 5%, or 9% of P_r
Power boost duration	5 s
Recovery duration	20 s
The effect of power boost duration	
Activation frequency	49.40 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of P_r
Power boost duration	Either 2.5, 5, 7.5, or 10 s
Recovery duration	20 s
The effect of the recovery duration	
Activation frequency	49.40 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of P_r
Power boost duration	5 s
Recovery duration	Either 10, 20, or 30 s

The parameter of deactivation frequency becomes useful only if the system frequency exceeds the deactivation frequency before the power boost phase is over. Then, the power boost deactivates and the function proceeds to the recovery phase. However, the effect of the deactivation frequency is not studied in this thesis since it is expected that the frequency does not very often recover within 10 s or so that is the typical duration of the power boost phase. Additionally, it is assumed that the deactivation frequency should be between 49.90–50.00 Hz according to the frequency target area for normal operation [27]. The effects of the power boost rise time and recovery phase duration cannot directly be studied with either of the wind power plant models. However, the steepness of the power boost rise can be analyzed by varying the activation frequency and the frequency for maximum power boost.

The power boost percentage and the power boost duration are among the most critical parameters for the performance of the inertia emulation provided by the control method of fixed power boost. Therefore, the parameters of power boost percentage and power boost duration are investigated first.

Power boost percentage

Figure 26 presents the active power output of a wind power plant connected at Pirttikylä substation and the corresponding grid frequency with three different values for power boost percentage. Also the benchmark, in which the inertia emulation function is off, is shown in the figure. Thus, the figure presents the effect of the power boost percentage on the performance of inertia emulation.

Figure 26 clearly demonstrates that the higher power boost percentage is, the better the inertia emulation can enhance the frequency nadir. However, the higher the power boost percentage is, the more important the recovery characteristics are for the power system security. If the active power drop during the recovery phase is not limited and stretched enough over a long period of time and the power boost percentage is high enough, a secondary frequency nadir will appear. In this case, even the power boost percentage of 5% of rated power causes too aggressive power drop during the recovery phase. It can also be observed according to the figure that the energy needed during the recovery phase is higher than the energy delivered during the power boost phase, and the higher the amount of energy delivered during the power boost phase is the more the energy needed during the recovery phase is increased.

Another interesting observation is that the secondary frequency nadir can be significantly deeper than the frequency nadir that would be reached without inertia emulation. This emphasizes the importance of reasonable power boost percentage and especially recovery characteristics. It is expected that the smoother the recovery characteristics are, the higher the power boost percentage can be without compromising the power system security. According to the figure, a reasonable power boost percentage in this case seem to be between 1–5% of rated power. Therefore, 3% of rated power is used for power boost percentage hereinafter.

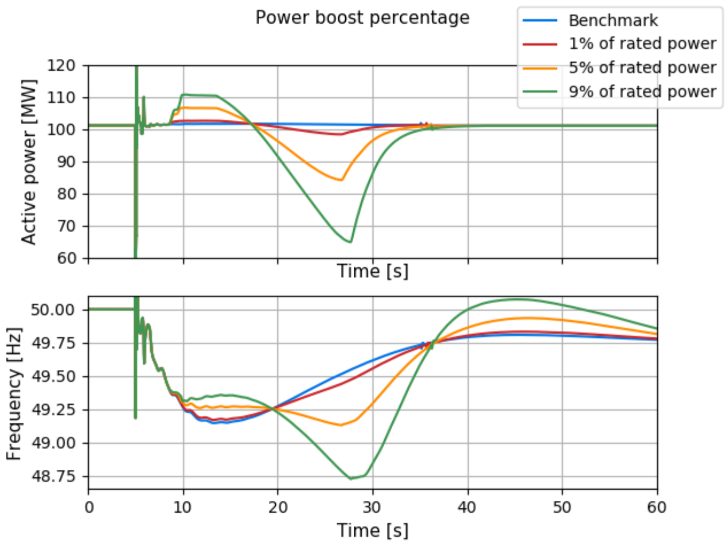

Figure 26. *Effect of power boost percentage on the performance of fixed power boost.*

Power boost duration

The effect of the power boost duration is shown in Figure 27. If the power boost duration is too short, the power boost phase undesirably ends before the frequency nadir is reached. With the settings used in this case, this occurs as the power boost duration is 2.5 s. If the power boost duration is too long relative to the power boost percentage and the inertia emulation function allows the power to decrease aggressively during the recovery phase, a secondary frequency nadir appears. With the settings used in this case, the secondary nadir can be avoided as the power boost duration is about 5 s or less.

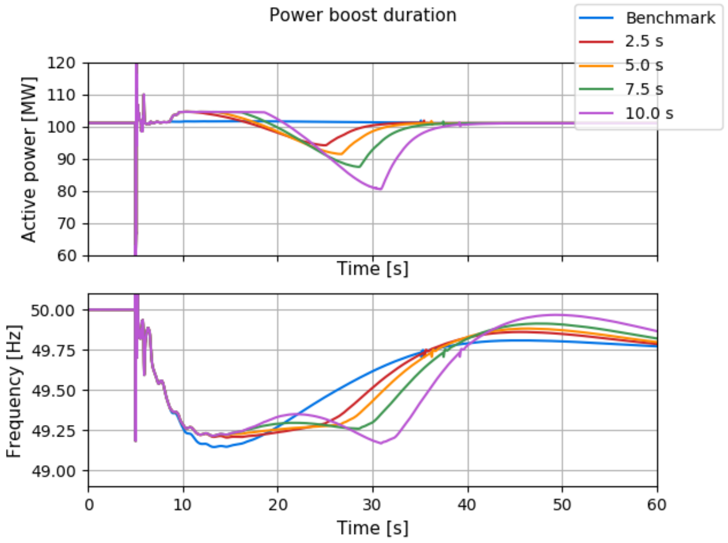

Figure 27. *Effect of power boost duration on the performance of fixed power boost.*

Recovery duration

Figure 28 demonstrates the effect of the recovery duration. By varying the recovery duration it is possible to adjust the recovery characteristics of the inertia emulation function. As shown in the figure, a secondary frequency nadir emerges as the power decreases too fast, and the risk of the secondary frequency nadir decreases as recovery duration increases. However, with the settings used in this case, it may not be reasonable to increase the recovery duration arbitrarily since it would delay the frequency recovery without improvement in the frequency nadir, for example.

It is also observed that the energy needed during the recovery phase increases as the recovery duration is prolonged with the wind power plant model used. This explains why the recovery duration of 20 s seems to yield the best performance of inertia emulation in this case. However, it is crucial to note that the prolonging the recovery phase with the wind power plant model used does not limit the power reduction during the recovery phase. Optimal recovery characteristics would in practice mean a prolonged recovery phase with limited power reduction. Therefore, it can be stated that the implementation of this parameter would require development.

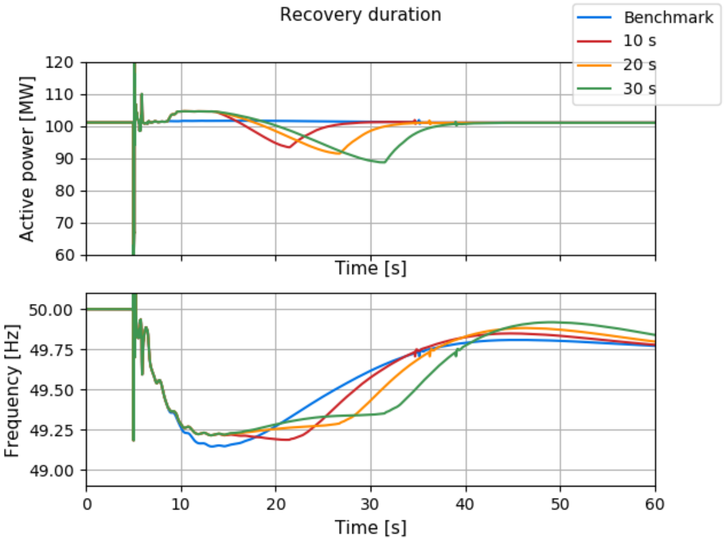

Figure 28. *Effect of the recovery duration on the performance of fixed power boost.*

Activation frequency

Figure 29 shows the effect of the activation frequency. With the settings used in this case, the impact of the activation frequency seems slight. It is however observed that the higher the activation frequency is, the better the RoCoF can be enhanced and the earlier the frequency recovers during the recovery period. In turn, the frequency nadir remains lower. This is caused by the power boost phase that ends too early, in other words the recovery phase and the active power reduction begin before the frequency has recovered enough. This could be fixed by increasing the power boost duration. However, the consequences of the change on the recovery characteristics must be taken into account. The observations, therefore, emphasizes the multidimensional task of the parametrization.

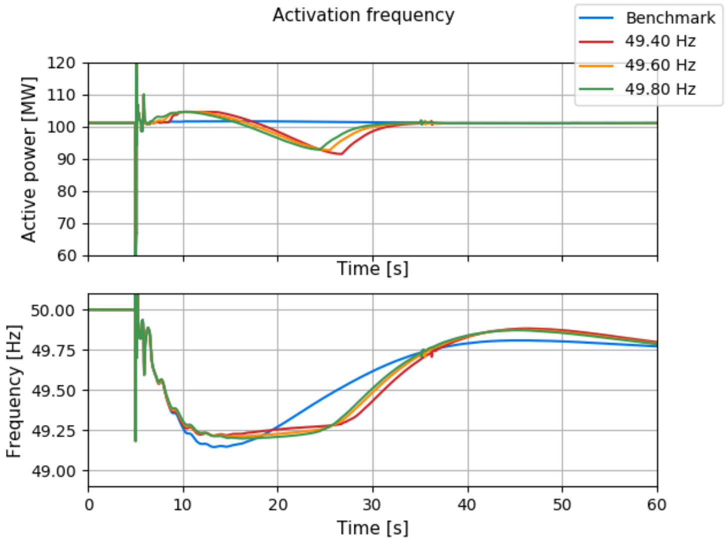

Figure 29. *Effect of activation frequency on the performance of fixed power boost.*

Frequency for maximum power boost

Figure 30 illustrates the effect of the frequency for maximum power boost. In order to study its effect, the activation frequency is exceptionally set to 49.60 Hz. The closer the activation frequency and the frequency for the maximum power boost are, the better the RoCoF is enhanced. In turn, as the activation frequency is lower, at 49.25 Hz, the power boost is provided at the right moment of time for the improvement of the frequency nadir.

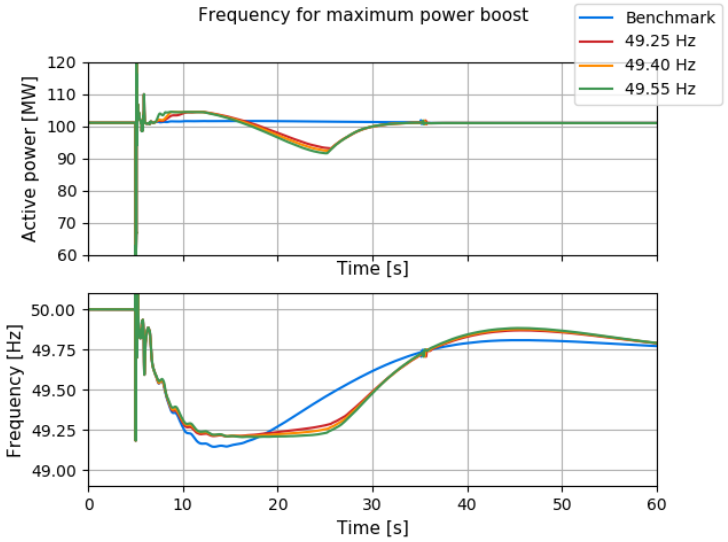

Figure 30. *Effect of frequency for maximum power boost on the performance of fixed power boost.*

Effect of the wind power capacity equipped with inertia emulation

Figure 31 presents the active power output of a wind power plant connected at Pirttikylä substation and the corresponding grid frequency. The capacities of the wind power plants are varied between the cases to achieve the desired total wind power capacity equipped with inertia emulation. Therefore, also the capacity of the wind power plant studied is varied. The parameter setting used is listed in Table 11. The frequency responses in the figure demonstrate that the importance of smooth recovery characteristics is highlighted as the wind power capacity equipped with inertia emulation is increased. A slight improvement in the frequency nadir is observed as the inertia emulating wind power capacity is increased when the control method of fixed power boost is used. This results from the power boost percentage which is retained constant and determined based on the rated active power of the wind turbine generators. The cases, however, are not entirely comparable since the system inertia and power generation differ among the cases.

Table 11. *Example of inertia emulation parameter setting.*

Fixed power boost	
Activation frequency	49.40 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of rated power
Power boost duration	5 s
Recovery duration	20 s

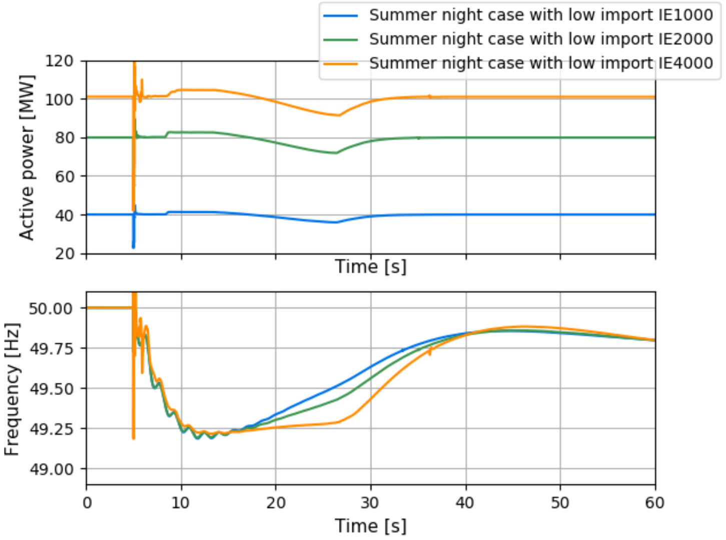

Figure 31. *Effect of wind power capacity equipped with the inertia emulation function when the control method of fixed power boost is used. The capacities of the wind power plant studied are approximately 40 MW, 80 MW, and 100 MW.*

6.1.3 Performance of proportional power boost

The performance of inertia emulation provided by the combination of the control methods of power boost proportional to frequency change and power boost proportional to frequency derivative is investigated next. In this thesis, this control method is called proportional power boost. The main control methods for providing inertia emulation are explained in Section 3.2.3 whereas the control method of proportional power boost is described in Section 5.2.1.

As mentioned above, the parametrization has a remarkable role in the performance of inertia emulation. The parameters analyzed are activation frequency, frequency for maximum power boost, power boost, power boost duration, and recovery duration. The values of the inertia emulation parameters used when studying their effects are listed in Table 12. The idea behind the parameter combinations selected and shown in Table 12 follows the same logic as explained in Section 6.1.2 regarding Table 10.

Some of the parameter values for the proportional power boost control method shown in Table 12 differ clearly from the parameter values for the fixed power boost control shown in Table 10. However, this does not effect on the analysis since the idea is to first study the effect of the parameters separately with each control method. After that, the frequency responses with different control methods are studied with the example parameter settings. As the frequency responses are observed to be quite similar, it can be stated that the difference of the parameter settings also demonstrate that the parameters may be understood differently between the inertia emulation modes or the different control methods may need to be parametrized differently.

As explained in Section 6.1.2, also the simulations shown in this section represent the simulations at the point of common coupling at one of the wind power plants connected at Pirttikylä substation unless otherwise specified.

Table 12. *Inertia emulation parameters used when studying the effect of the parameters on the performance of the proportional power boost control.* P_r *= rated power.*

The effect of activation frequency	
Activation frequency	Either 49.30, 49.50, or 49.70 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of P_{r}
Power boost duration	20 s
Recovery duration	0 s (not relevant)
The effect of frequency for maximum power boost	
Activation frequency	49.40 Hz
Frequency for maximum power boost	Either 49.10, 49.20, or 49.30 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of P_{r}
Power boost duration	20 s
Recovery duration	0 s (not relevant)
The effect of power boost percentage	
Activation frequency	49.30 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	Either 5%, 15%, or 25% of P_{r}
Power boost duration	20 s
Recovery duration	0 s (not relevant)
The effect of power boost duration	
Activation frequency	49.30 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of P_{r}
Power boost duration	Either 5, 10, 15, or 20 s
Recovery duration	0 s (not relevant)
The effect of the recovery duration	
Activation frequency	49.30 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of P_{r}
Power boost duration	20 s
Recovery duration	Either 0, 5, 10, or 15 s

Activation frequency

Figure 32 shows the active power output of a wind power plant connected at Pirttikylä substation and the corresponding grid frequency with three different values for the activation frequency. Also the benchmark, in which the inertia emulation function is off, is shown in the figure. Thus, the figure presents the effect of the activation frequency on the performance of inertia emulation.

According to the figure, the higher the activation frequency is, the better the inertia emulation improves the RoCoF. However, the improvement in the frequency nadir is at higher priority in the Nordic power system. In this connection, the figure clearly demonstrates that if the power boost is proportional to the absolute frequency change and the frequency derivative and, as a consequence, the power boost phase lasts only a few seconds, the power boost phase must take place precisely at the right moment. Otherwise the power boost phase can already be over before the frequency nadir has been reached, as it occurs when the activation frequency is 49.50 or 49.70 Hz. Another example of undesired behavior is that the frequency nadir is reached before the inertia emulation has provided its power contribution. Thus, it is desirable that the major power contribution occurs just before the frequency nadir, and for the same reason, the activation frequency of 49.30 Hz offers the best performance in this case.

In a real system, the power boost phase of a longer duration would, however, be practical to make the inertia emulation function useful in different types of disturbance events. The duration of the power boost phase cannot, however, be controlled by a parameter in this case since the power boost of the control method of proportional power boost is determined by the frequency behavior. This is further discussed below when analyzing the effect of the parameter of power boost duration. On the other hand, the feature of the power boost being proportional to the frequency change and derivative enables the control method to adjust to different disturbance events.

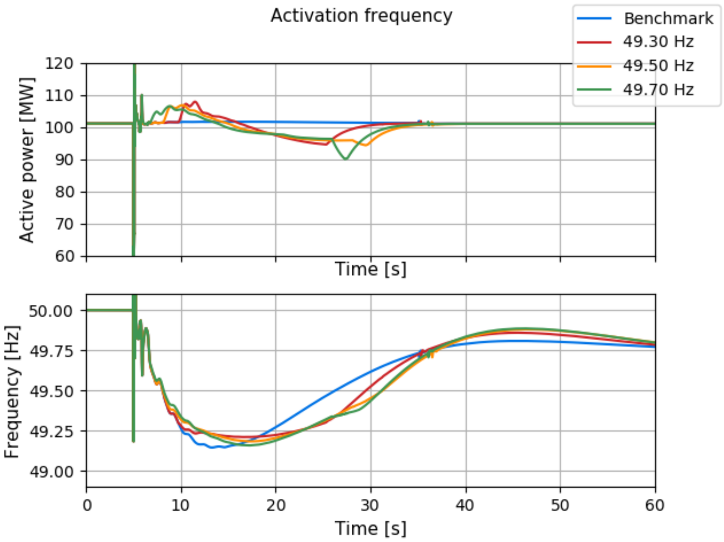

Figure 32. *Effect of activation frequency on the performance of proportional power boost.*

Frequency for maximum power boost

The effect of the frequency for maximum power boost is presented in Figure 33. For this analysis the activation frequency of 49.40 Hz is used instead of the activation frequency of 49.30 Hz which is above observed to offer the best performance in this case. According to the figure, a good performance of inertia emulation is achieved when the frequency for maximum power is at the lowest value studied (49.10 Hz). Then, the active power contribution is provided relatively steadily during the power boost phase and the power contribution ends as the frequency nadir is reached. If both the activation frequency and the frequency for maximum power boost are high, the wind turbine generators in the wind power plant release a massive amount of energy in a couple of seconds which results in a power boost phase that lasts only some seconds. Consequently, the power boost phase occurs too early relative to improving the frequency nadir.

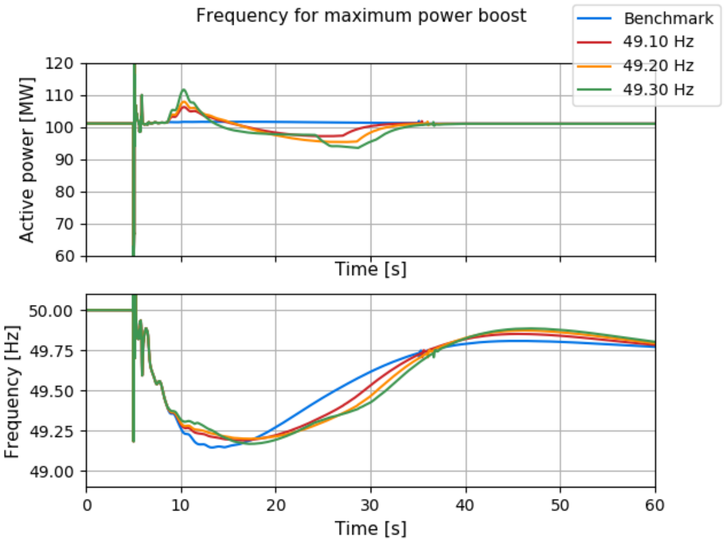

Figure 33. *Effect of frequency for maximum power boost on the performance of proportional power boost.*

Power boost percentage

Figure 34 illustrates the effect of the power boost percentage on the performance of the proportional power boost control. The figure clearly shows that the capability of inertia emulation to improve the frequency nadir is minor if the power percentage is low. In turn, the higher the power boost percentage is, the more the frequency nadir can be improved. The drawback of increasing the power boost percentage is the delay in the frequency recovery. According to the simulations, owing to the short power boost phase and the smooth active power drop during the recovery phase the risk of a secondary frequency nadir appears lower with inertia emulation controlled by proportional power boost than by fixed power boost.

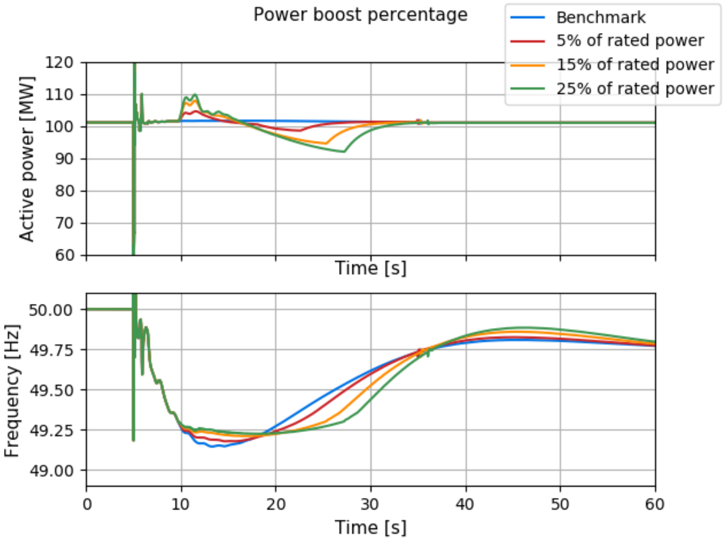

Figure 34. *Effect of power boost percentage on the performance of proportional power boost.*

Power boost duration

The effect of the power boost duration is demonstrated in Figure 35. In the case of proportional power boost, shortening or lengthening the power boost duration does not change the duration of the active power provision. However, in this case, the power boost duration is understood differently. Namely, as the power boost is both proportional to the frequency change and the frequency derivative, the duration of the power boost provision cannot be controlled by a pre-defined the parameter of power boost duration since the provision of the additional power ends as the frequency starts to recover. However, by lengthening the power boost phase duration, the beginning of the recovery phase can be postponed up to a certain point in this manufacturer-specific implementation. This is discussed below.

If the parameter of power boost duration is 5–10 s, a secondary frequency nadir is developed due to the steep active power drop after the active power provision. However, increasing the parameter of power boost duration from 15 s to 20 s does not affect much on the performance of the inertia emulation as merely a slight difference is noticed in the recovery phase. In order to avoid a secondary frequency nadir, a reasonable value for the parameter of power boost duration is between 15–20 s according to the figure.

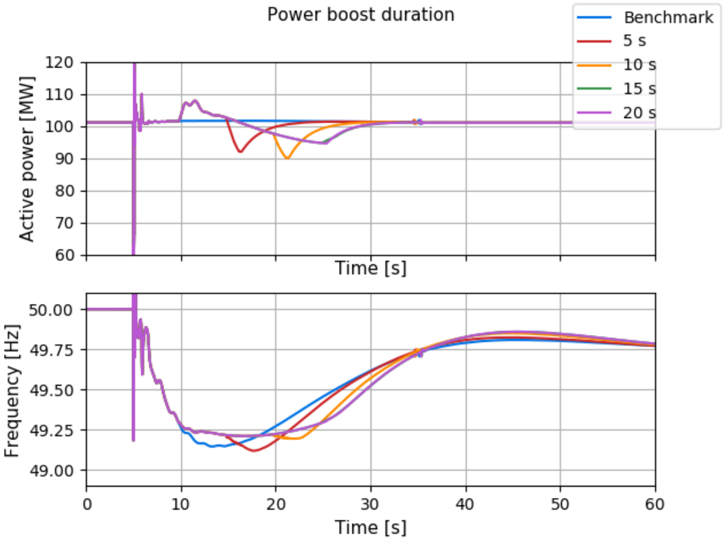

Figure 35. *Effect of power boost duration on the performance of proportional power boost.*

Recovery duration

As Figure 36 demonstrates, the recovery duration is discovered to be irrelevant for the manufacturer-specific implementation of proportional power boost. There is no difference in the simulation results when the recovery duration is 0, 5, 10 or 15 s. This may be due to the unfinished model or inertia emulation function development. Unfortunately, the user cannot investigate the issue further because the model utilized is a so-called black-box model. Therefore, the parameter of recovery duration is 0 s in most of the simulations presented in this section as Table 12 shows. It is, however, obvious that a smooth recovery characteristics are necessary for system security.

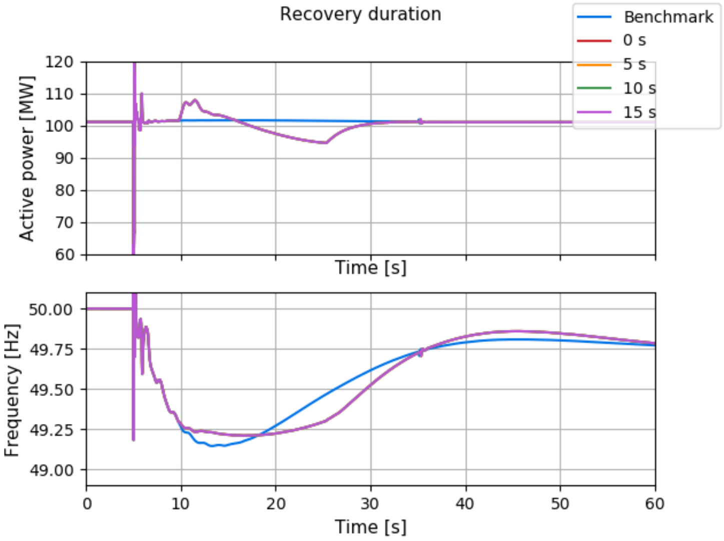

Figure 36. *Effect of recovery duration on the performance of proportional power boost.*

Effect of the wind power capacity equipped with inertia emulation

Figure 37 presents the active power output of a wind power plant connected at Pirttikylä substation and the corresponding grid frequency. The capacities of the wind power plants are varied between the cases to achieve the desired total wind power capacity equipped with inertia emulation. Therefore, the capacity of the wind power plant studied is varied, too. The parameter setting used is listed in Table 13. When the control method of proportional power boost is used to provide inertia emulation, the amount of additional active power is determined by the absolute frequency change and frequency derivative. Thus, the frequency nadirs observed in the different cases are in the same order with each other. Nevertheless, the frequency responses in the figure demonstrate that the importance of smooth recovery characteristics is highlighted as the wind power capacity equipped with inertia emulation is increased.

Table 13. *Example of inertia emulation parameter setting.*

Proportional power boost	
Activation frequency	49.30 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of rated power
Power boost duration	20 s
Recovery duration	0 s (not relevant)

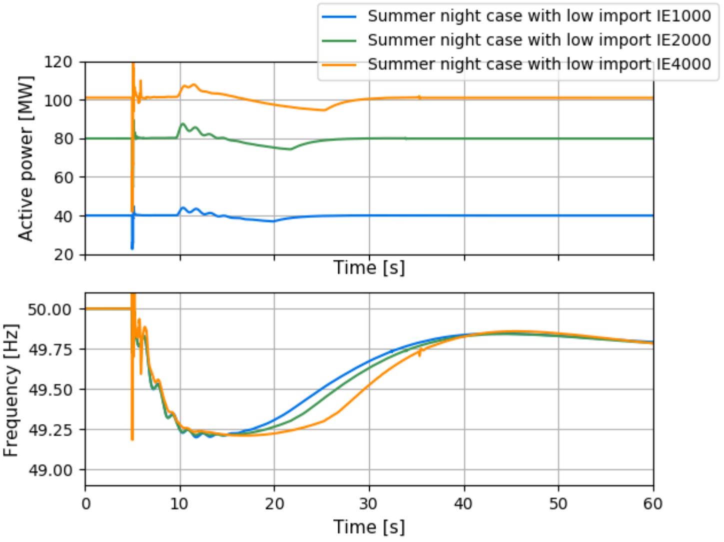

Figure 37. *Effect of wind power capacity equipped with the inertia emulation function when the control method of proportional power boost is used. The capacities of the wind power plant studied are approximately 40 MW, 80 MW, and 100 MW.*

Additional observations

Figure 38 shows the active power outputs of different wind power plants and the corresponding local frequency measurements. The figure demonstrates that the active power outputs of the wind power plants only differ slightly though the wind power plants locate geographically around a wide area and each of them use a local frequency measurement as their control signal. Since the fault and the disconnecting generation unit locate the closest to the wind power plants connected at Pirttikylä substation, the spikes in the frequency during the fault exciting the disturbance event are the highest at the wind power plants at Pirttikylä.

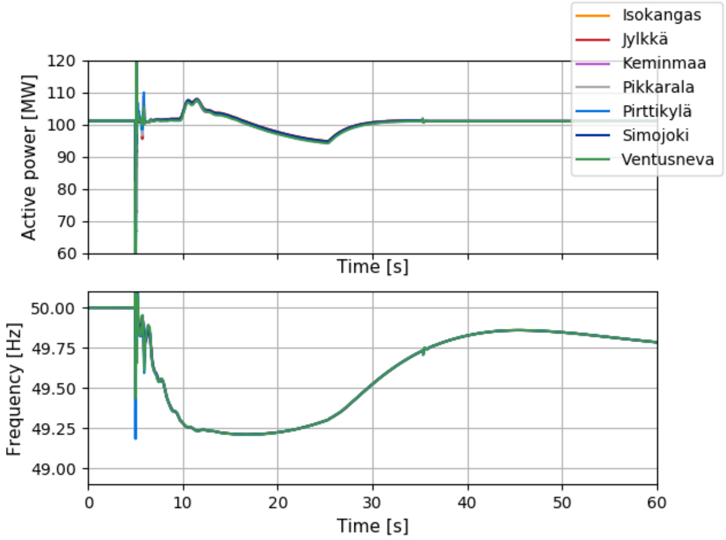

Figure 38. Active power outputs of different wind power plants and corresponding local frequency measurements.

As expected, the frequency oscillations caused by the power oscillations are reflected to the power contribution provided during the power boost phase when the control method of proportional power is used and the delay between the frequency measurement and the control is fast enough. The oscillating frequency signal does not effect on the performance of the inertia emulation. This finding is revealed in all the figures presented above. The performance of proportional power boost in a power flow case with power oscillations is discussed more in Section 6.2.2.

6.1.4 Analysis

The performance of fixed power boost and proportional power boost as well as the effect of the parametrization on the performance are inspected above in Section 6.1.2 and Section 6.1.3 correspondingly. The impact of inertia emulation on the power system depends substantially on the inertia emulation control method and its implementation as well as on the inertia emulation parametrization.

There are several findings that apply both to fixed power boost and proportional power boost. Most importantly, if the recovery characteristics are not smooth enough, the power boost percentage and the power boost duration must be set with caution or restricted in order to avoid the development of a secondary nadir. This, however, means that the frequency nadir is not improved as much as it could be and the whole potential of the inertia emulation is not harnessed. Additionally, if the power boost duration lasts only some seconds, the risk of inertia emulation not to fit in different disturbance cases increases. Namely, the risk of the power boost phase either ending too early (before the frequency nadir is reached) or not beginning early enough (the frequency nadir is reached before the full power contribution) increases if the power boost duration is short.

The activation frequency and frequency for maximum power boost as well as their difference determine characteristics of the early stage of the power boost phase. Their effect on the inertia emulation performance is emphasized when the duration of the power boost phase is in the order of 5 s. Then, it is difficult or even impossible to parametrize the activation frequency and frequency for maximum power boost to provide good performance in different disturbance scenarios as explained above.

For fixed power boost, the recovery characteristics can partly be adjusted by varying the recovery duration. The simulations prove that a longer fall time of the power is recommended since it stretches the duration of the recovery phase and consequently decreases the risk of the secondary frequency nadir. For proportional power boost, in turn, the parameter of the recovery duration with the wind power plant model used is noticed to be badly implemented. This is most likely due to the incomplete development of the model or proportional power boost control method. Nevertheless, a longer recovery duration is recommended regardless of the control method.

All in all, the simulations examined in Section 6.1.2 and Section 6.1.3 demonstrate the multidimensionality of the inertia emulation parametrization. Additionally, the simulations prove that if the inertia emulation is not implemented well with an appropriate level of flexibility and with smooth recovery characteristics, a satisfactory inertia emulation performance in different disturbance events is difficult to achieve without adjusting the parameters again. However, if the inertia emulation would be required and utilized in a real system, the inertia emulation settings would not be changed to fit a specific disturbance event but the same settings should satisfactorily fit in different disturbances and power flow situations. These observations emphasize TSO's responsibility to set the inertia emulation requirement precisely enough so that the function performs as desired during different disturbance events and power flow situations when the requirement is met.

With the settings shown in Table 14 it is possible to provide active power support during the power boost phase without the occurrence of a secondary frequency nadir during the recovery phase due to dramatic active power reduction and without remarkable delay in the frequency recovery when Olkiluoto 3 nuclear unit disconnects from the system as a result of a three-phase short circuit. However, due to the weaknesses of the inertia emulation implementation the settings listed in the table do not yield the optimal inertia emulation performance. The basis of drawing the suggestions for inertia emulation requirement setting is to formulate the requirement to be robust enough for different power flow and disturbance situations. Therefore, it is necessary that the power boost phase duration can be set long enough so that the power boost would be provided at the right moment and aligned with the lowest frequencies during the disturbance event. Additionally, the control method of proportional power boost adaptive to different disturbance events is recommended for the same reason as explained in Section 7.2.

Table 14. *Examples on inertia emulation parameters when Olkiluoto 3 disconnects as a result of a three-phase short circuit in summer night case with low import.*

Fixed power boost	
Activation frequency	49.40 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of rated power
Power boost duration	5 s
Recovery duration	20 s
Proportional power boost	
Activation frequency	49.30 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of rated power
Power boost duration	20 s
Recovery duration	0 s (not relevant)

As mentioned above, it is desirable that the inertia emulation requirement is formulated so that the same settings are suitable for different disturbances and power flow situations. Especially the most severe N−1 contingencies combined with the low inertia situations are the most important for the objective of inertia emulation. In the context of this thesis, the summer night case with low import represents and the summer night case with maximum export are the worst situations for frequency stability since the system inertia in these cases is in the order of 120−130 GWs. The parameters shown in Table 14 are found by studying the disconnection of Olkiluoto 3 as a result of three-phase short circuit. The disconnection of Olkiluoto 3 as a result of three-phase short circuit belong among the most severe disturbance events. Thus, the inertia emulation settings shown in the table are fine-tuned for one of the most severe disturbance events which means that the settings do not offer the best performance in other disturbance events or in other power flow cases. Because the aim of inertia emulation would be decreasing the risk of under-frequency load shedding activation and the risk of a system blackout, it particularly is appropriate that the best performance is yield in the most severe disturbances and in low inertia situations.

Figure 40 demonstrates the inertia emulation performance of the manufacturer-specific wind power plant used in different disturbance events with the example parameter settings shown in Table 14. The figure highlights that the power contribution provided during the power boost phase depends on the specific disturbance event when proportional power boost is used whereas the power boost remains constant between the cases when fixed power boost is used.

Another important observation regarding the differences of the control methods is the relation of the control method and the wind power capacity equipped with inertia emulation function. Namely, as Table 15 reveals, the impact of the inertia emulation on the frequency nadir improvement depends on the control method when the inertia emulating wind power capacity is increased. The effect of inertia emulation on the frequency nadir is directly proportional to the wind power capacity when fixed power boost is used whereas the effect is steadier when proportional power boost is used.

Table 15. *Examples on the frequency nadir improvements. Cases: summer night case with low import IE1000, summer night case with low import IE2000, and summer night case with low import IE4000.*

Wind power capacity equipped with inertia emulation function	System inertia	Frequency nadir improvement	
		Fixed power boost, 3% of the rated power	Proportional power boost, the parameter of power boost percentage 15%
1000 MW	125 GWs	0.017 Hz	0.049 Hz
2000 MW	122 GWs	0.034 Hz	0.054 Hz
4000 MW	121 GWs	0.071 Hz	0.069 Hz

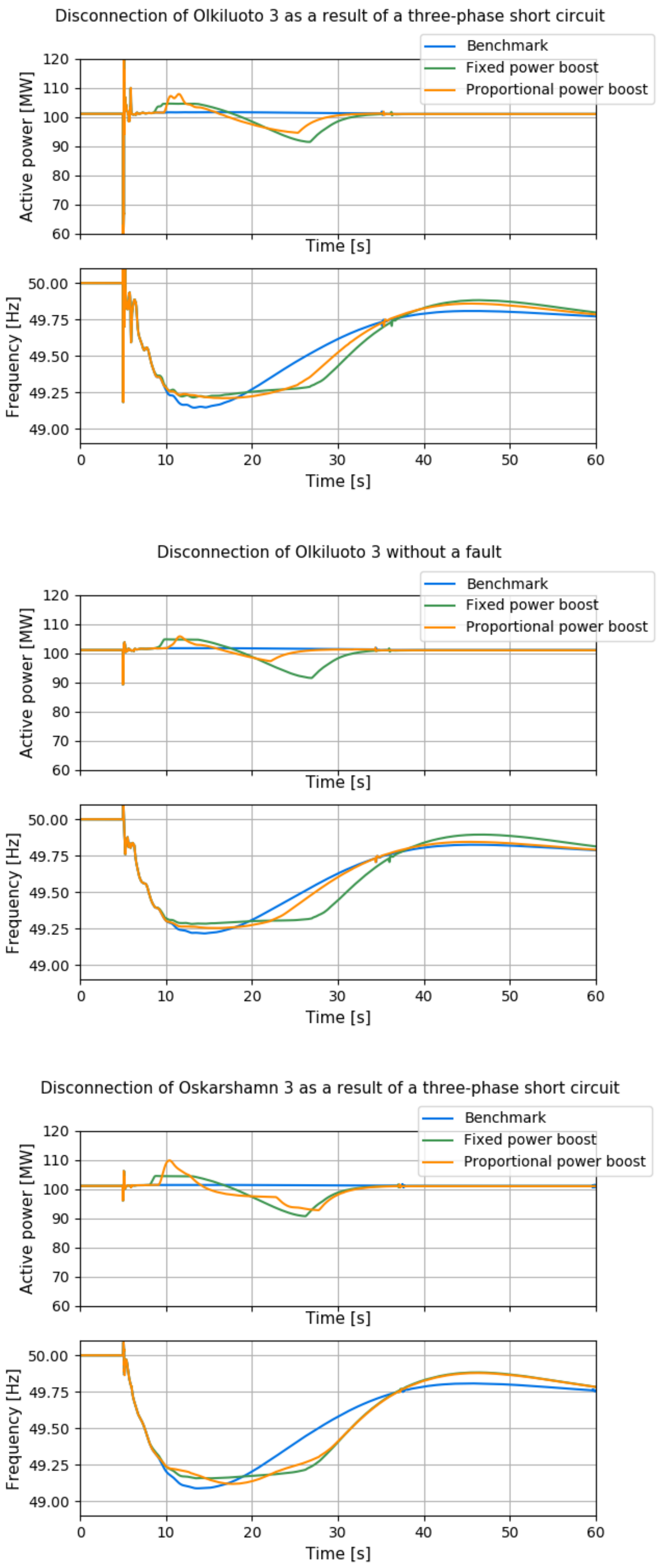

Figure 39. *Examples on inertia emulation performance in different disturbance events. Case: summer night case with low import IE4000.*

6.2 Impact of inertia emulation on other stability criteria

The aim of requiring an inertia emulation functionality from wind power plants in the Nordic power system would be to enhance frequency stability of the system with high wind power penetration level. However, it is not practical to set a requirement to improve frequency stability if it would weaken the power system stability relative to other stability criteria. Therefore, it is necessary to ensure that the inertia emulation functionality does weaken neither voltage stability nor damping of power oscillations.

6.2.1 Impact on voltage stability

As described in Section 5.1.2, the voltage stability can be emphasized by utilizing the winter case with maximum AC import from Sweden to Finland. The disturbance studied is the disconnection of Olkiluoto 3 nuclear unit (1300 MW with system protection scheme disconnecting 300 MW of load) as a result of a three-phase short circuit at a nearby bus bar.

The inertia in the winter case with maximum AC import is in the order of 270 GWs, and in the benchmark, the frequency reaches its minimum of 49.55 Hz. This frequency nadir is clearly higher than the frequency nadirs in the order of 49.20 Hz that are reached in the summer night cases. Therefore, the activation frequency and the frequency for maximum power boost must be adjusted in this case to enable the inertia emulation to activate and study its effect on the voltage stability in a case in which the voltage stability is emphasized. By this change it is possible to analyze the effect of inertia emulation on the voltage stability in a power flow case in which the voltages are initially low because of the high transmission from Sweden to Finland and further from Northern Finland to Southern Finland. It is important to note that the inertia emulation settings would not be changed in a real power system. In this case, the change is executed solely on the theoretical purposes. The effect of the inertia emulation on the voltage stability in other power flow cases remains similar is expected to remain similar.

The values of the inertia emulation parameters used for fixed power boost and for proportional power boost are listed in Table 16. Figure 40 shows the effect of inertia emulation on voltage stability.

Table 16. *Inertia emulation parameters used when studying the effect of inertia emulation on the voltage stability.*

Fixed power boost	
Activation frequency	49.70 Hz
Frequency for maximum power boost	49.65 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of rated power
Power boost duration	5 s
Recovery duration	20 s
Proportional power boost	
Activation frequency	49.65 Hz
Frequency for maximum power boost	49.60 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of rated power
Power boost duration	20 s
Recovery duration	0 s (not relevant)

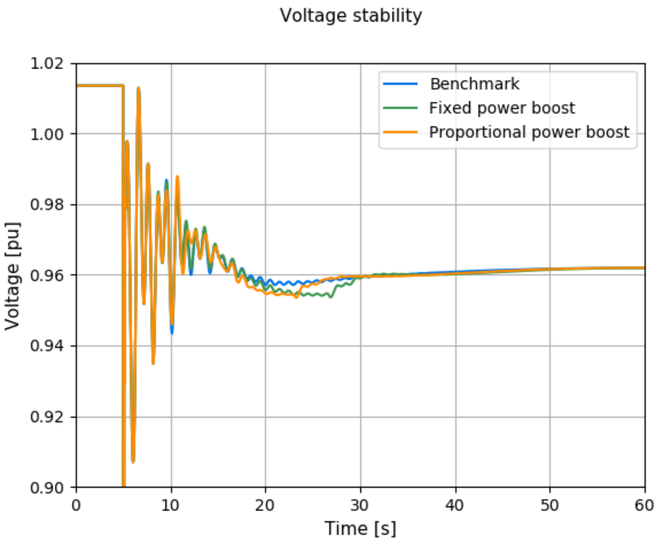

Figure 40. *Effect of inertia emulation of fixed power boost and proportional power boost on voltage stability at Alajärvi substation in Southern Finland. Case: winter case with maximum import. Disturbance: disconnection of Olkiluoto 3 as a result of a three-phase short circuit.*

As Figure 40 reveals, the inertia emulation function of Enercon neither by fixed power boost control nor proportional power boost does in practice effect on the voltage stability. The first voltage swings after the fault (at 5–9 s) are not affected by the inertia emulation since the functionality is not yet activated. After the activation of inertia emulation (at 9–14 s) the voltage swings are slightly diminished in comparison with the benchmark. In turn, the voltage level during the recovery phase (18–30 s) is lower than the benchmark voltage. By the fixed power boost control, for instance, the deviation of the voltage from the benchmark depends on the percent of the power boost. The higher the power boost percentage is, the lower the voltage appears during the power boost phase. These observations are explained next.

As all the wind power plants equipped with the inertia emulation function locate in Finland in the simulations, the power generation in Finland is temporarily increased during the power boost phase. As a result, the power transmission from Sweden to Finland as well as the transmission from Northern Finland to Southern Finland decrease resulting in slightly diminished voltage swings at Alajärvi substation in Southern Finland. In turn, the power transmissions from Sweden to Finland and from Northern Finland to Southern Finland are increased during the recovery phase since the power generation of the inertia emulating wind power plants located in Finland temporarily decreases. The high transmissions increase the reactive power consumption of the power lines which results in low voltages and increased demand for reactive power support. This denotes that if the wind power plants equipped with inertia emulation function would locate all around the Nordic power system, the transmission would not be affected by the inertia emulation phases and thus the situation would be even better.

According to Fingrid's grid code for generators, the generating units must remain connected to the grid for at least 30 min with system frequency of 47.5–49.9 Hz and voltage of 0.95–1.05 pu [32][33]. In the winter case with maximum AC import, the frequency recovers to the normal state target area of 49.9–50.1 Hz within a minute and the voltage do not decrease below 0.95 pu with a reasonable percent of the power boost. Therefore, the effect of the lower voltage during the recovery phase seem not significant for voltage stability. It is however important to take the possibility of this effect into account. Moreover, some local issues are also possible but out of the scope of this study.

6.2.2 Impact on damping of power oscillations

In the Nordic power system, there appear inter-area power oscillations when the power transmission through the AC connections from Finland to Sweden is high. The damping of power oscillations is therefore investigated by simulations executed using the summer night case with maximum export and inertia emulating wind power capacity of 4000 MW. Table 17 shows the inertia emulation parameters used when studying the effect of inertia emulation on the damping of power oscillations.

Table 17. *Inertia emulation parameters used when studying the effect of inertia emulation on the damping of inter-area power oscillations.*

Fixed power boost	
Activation frequency	49.40 Hz
Frequency for maximum power boost	49.35 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	3% of rated power
Power boost duration	5 s
Recovery duration	20 s
Proportional power boost	
Activation frequency	49.30 Hz
Frequency for maximum power boost	49.20 Hz
Deactivation frequency	49.90 Hz
Power boost percentage	15% of rated power
Power boost duration	20 s
Recovery duration	0 s (not relevant)

Figure 41 and Figure 42 demonstrate the effect of inertia emulation on the damping of power oscillations. The results in Figure 41 represent the combination of the disconnections of Forsmark 3 and Fenno-Skan 2 as a result of a three-phase short circuit at a nearby bus. In turn, the results in Figure 42 are produced by simulating the disconnection of Olkiluoto 3 as a result of a three-phase short circuit.

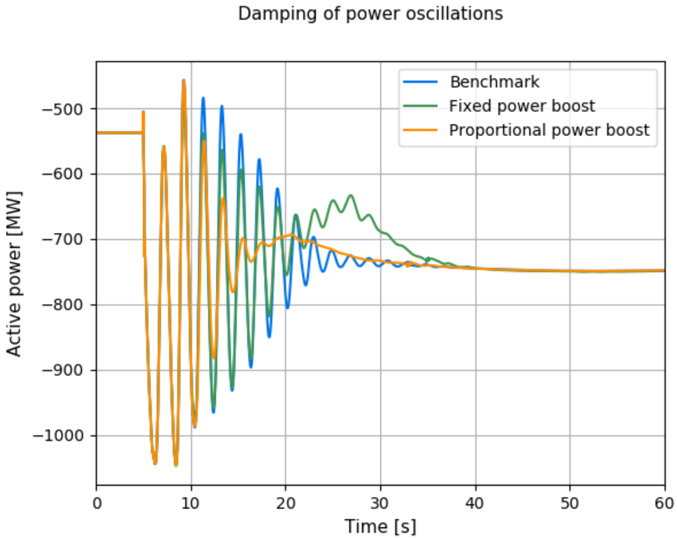

Figure 41. *Effect of inertia emulation on the damping of inter-area power oscillations on an AC interconnector between Sweden and Finland. Case: summer night case with maximum export. Disturbance: disconnections of Forsmark 3 and Fenno-Skan 2 as a result of a three-phase short circuit.*

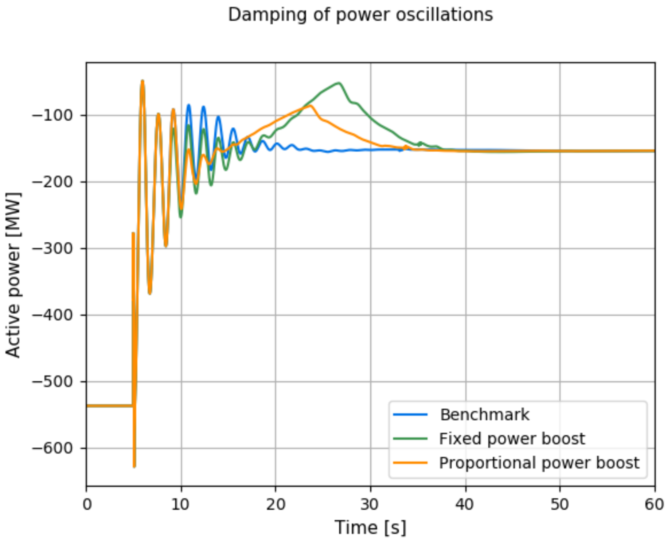

Figure 42. *Effect of inertia emulation on the damping of power oscillations on an AC interconnector between Sweden and Finland. Case: summer night case with maximum export. Disturbance: disconnection of Olkiluoto 3 as a result of a three-phase short circuit.*

According to the figures, the inertia emulation by fixed power boost control slightly improves the damping of power oscillations by mainly decreasing the amplitude of the oscillations. The inertia emulation by proportional power boost control, however, significantly improves the damping by both decreasing the amplitude of the oscillations and shortening the time that it takes until the oscillations end. The first oscillations between 5–10 s are not affected by the inertia emulation in either of the cases since the function is not activated immediately after the fault but is activated as the frequency falls below the activation frequency.

According to Figure 42, the AC transmission from Sweden to Finland increases linearly at 17–27 s (green curve) and 15–25 s (orange curve). This is due to the power decrease of the wind power plants equipped with inertia emulation during the recovery phase. When the rotational speeds of the wind power plants start to accelerate back to the optimum value, the wind power plants begin to generate more power and consequently the AC transmission begins to decrease. The same phenomenon but significantly slighter can be seen in Figure 41, too.

The reason why the control method of proportional power boost effectively improves the damping of power oscillations originates from the nature of the control. Namely, the amount of power boost follows both the frequency change and the frequency derivative. Thus, as the power oscillations causes the frequency to decrease, the proportional power boost controls the wind power plant output power to increase compensating the oscillations in the frequency, and the other way around. However, this is only true when the power control is fast enough, in other words, when the delay between the frequency measurement and the power control is short enough. This issue is emphasized in Figure 43.

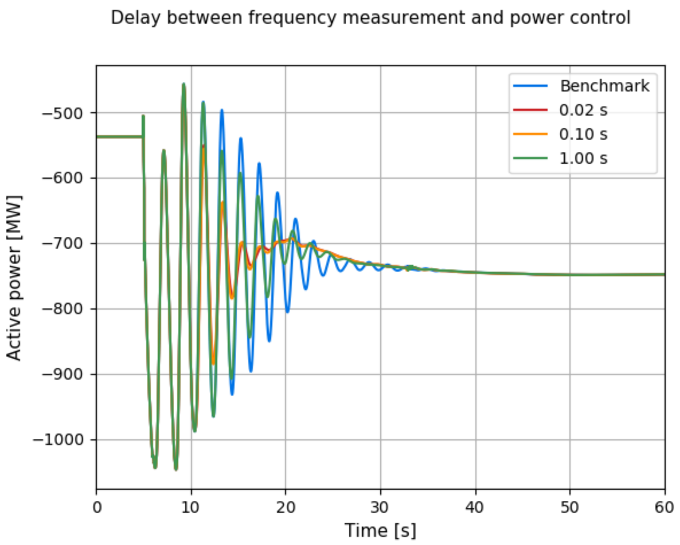

Figure 43. *Effect of the delay between the frequency measurement and the power control on the damping in power boost on an AC interconnector between Sweden and Finland. Case: summer night case with maximum export. Disturbance: disconnections of Forsmark3 and Fenno-Skan 2 as a result of a three-phase short circuit. Control method: proportional power boost.*

According to Figure 43, the proportional power boost control improves the damping of oscillations effectively as the delay is between 0.02–0.10 s. In turn, the improvement in the damping is only minor as the delay is increased to 1.00 s. In that case, the control of the power is not fast enough and consequently the increase or decrease in the wind power plant output power do not compensate the frequency oscillations. Moreover, if the delay between the frequency measurement and the power control was 1/0.3 Hz = 3.3 s, that is the cycle time of the dominant inter-area power oscillation mode in the Nordic power system [55], the inertia emulation function controlled by proportional power boost could even amplify the oscillations. The importance of the delay is therefore crucial.

6.2.3 Analysis

The effect of inertia emulation on the voltage stability and the damping of power oscillations in the Nordic power system is studied above in Section 6.2.1 and Section 6.2.2.

The results in Section 6.2.1 show that the inertia emulation functionality seem not impact on the voltage stability of the Nordic power system whether the control method used is fixed power boost or proportional power boost. The results presented in Section 6.2.2 prove that the inertia emulation can outstandingly improve the damping of power oscillations if the function is controlled by proportional power boost and the delay between the frequency measurement and power control does not exceed 0.1 s. In turn, the improvement in the damping achieved by fixed power boost is clearly slighter than by proportional power boost.

According to these observations, the usage of the inertia emulation functionality does not contradict the voltage and angular stability regardless of the control method. In terms of the overall stability of the Nordic power system, the control method of proportional power boost is more recommended.

In this thesis, the advantages of the proportional power boost regarding the increased damping of the power oscillations is however analyzed from the power system point of view. This means that it is not analyzed whether the oscillations in the wind power plant output power compensating the power oscillations in the system can cause remarkable mechanical stress to the wind turbine generator or its drive train. This issue should be considered by the wind turbine manufacturers.

6.3 Inertia emulation in conjunction with fault ride through

The inertia emulation function in conjunction with the fault ride through function is discussed in this section.

6.3.1 Impact of fault ride through

The aim of the fault ride through function (FRT) is primarily to ensure that the wind power plant does not immediately disconnect from the grid as a result of a fault in the nearby. In addition, it typically provides voltage support by injecting the reactive power contribution during the fault event. Even though the actual fault ride through operation occurs during the fault, it should be noted that the optimal recovery time for the fault ride through function for the wind power plants in the Finnish power system is 2–3 s [48] which could occur concurrently with the activation of inertia emulation power boost. As described in Section 3.2.5, the active power contribution provided during the power boost phase of inertia emulation may contradict the reactive power provision if the wind power plant is operating close to the apparent power limit of the converter, and therefore, it must be selected whether the active power or reactive power shall be prioritized in such a situation.

In order to study how the inertia emulation capability and fault ride through work together when the wind power plant operates at rated active power, a reasonable simulation is executed. First, a short circuit fault is produced at the high voltage side of the main transformer of Olkiluoto 3 nuclear unit causing the disconnection of the unit. The short circuit causes the voltage to decrease nearby the fault location, and therefore, it is followed by the activation of the fault ride through function at the nearby wind power plant. As a result of the disconnection, there is a significant active power deficit, and thus, the inertia emulation function is activated according to the frequency signal received by the converter.

Figure 44 shows the active and reactive power outputs of a wind power plant when the disconnection of Olkiluoto 3 occurs at 5 s as a result of a three-phase short circuit. The wind power plant studied is one of the wind power plants connected to Pirttikylä substation which is the southernmost substation of the eight substations studied. In this case, the power flow case represents the winter case with maximum import so that the demand for voltage support is more significant than in the summer cases. The parameter settings of inertia emulation used in this case are listed in Table 16.

The figure demonstrates that, in this example representing one of the dimensioning fault events in the Nordic power system, the reactive power is restricted by its upper limit of 36 MW only during the first oscillations during which the inertia emulation is not yet activated. The figure shows that if the active power recovery of fault ride through is immediate, the consecutive operation of the fault ride through and inertia emulation functions do not cause contradictions in active and reactive power provision.

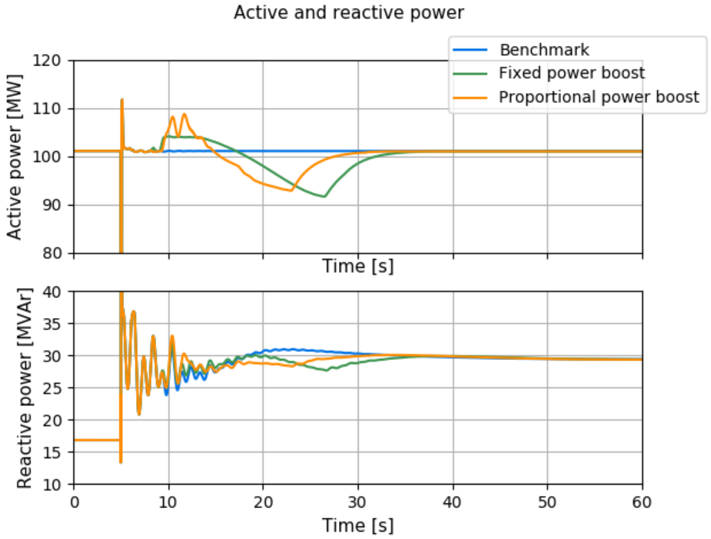

Figure 44. *Active and reactive power outputs of a wind power plant. Case: winter case with maximum import. Disturbance: disconnection of Olkiluoto 3 as a result of a three-phase short circuit.*

6.3.2 Analysis

The optimal recovery time of the fault ride through function for the wind power plants in the Finnish power system is 2–3 s [48]. The frequency nadir is typically reached at 5–8 s in the Nordic power system, and thus, a reasonable activation time of the inertia emulation power boost is probably be in the order of 2–4 s. This means it is possible that the functions are operating simultaneously. Therefore, it should be decided whether to prioritize the active or reactive power during the simultaneous under-frequency event and a fault causing low voltages locally nearby the fault location. In other words, it should be decided whether to prioritize the power boost of inertia emulation or the active power recovery of fault ride through if the functions occur to be active simultaneously.

It is not possible to adjust the active power recovery time of the fault ride through function with the wind power plant model used. Therefore, it can only be stated that the fault ride through and inertia emulation functions do not contradict when the recovery of the fault ride function is immediate and the activation time of the inertia emulation function is in the order of 2–4 s. Therefore, it is recommended for future work to analyze the behavior of the inertia emulation and fault ride through functions together when the recovery of fault ride through and the activation of inertia emulation may occur simultaneously.

As the wind power generation is typically spread around in the system, it is thus possible that the wind turbine generators equipped with inertia emulation in a wind power plant close to the fault location would operate at rated power simultaneously when a dimensioning fault occurred. In this connection, one should however bear in mind that the voltage dip only impacts on the wind power plants close to the fault location. Nevertheless, the possibility of this kind of an issue must be taken into account when formulating the possible inertia emulation requirement.

7. SUMMARY OF THE RESULTS AND SUGGESTIONS FOR REQUIREMENT SETTING

This chapter summarizes and evaluates the main results of this thesis. Additionally, the suggestions for requirement setting are collected.

7.1 Summary of the results

As described in Section 1.2, the primary objective of this thesis is to study the inertia emulation functionality of converter-connected wind power plants in the Nordic power system to be able to analyze the usefulness and performance of the function. The issues covered contain the capacity of the inertia emulating wind power generation needed to improve the frequency nadir and recommendation for the control method as well as the availability and limitations of the function, the parametrization of the function, the performance of the function in a power system with power oscillations, and consistency of the function with the selected stability criteria and with the fault ride through function.

First of all, the capacity of the inertia emulating wind power generation needed to improve the frequency nadir depends on several factors. Among them are the level of the improvement desired, the control method, the power boost duration, the power boost percentage and its base that is either the rated power or the actual pre-activation power of the wind power plant. It is discovered, for example, that with the wind power capacity of 4000 MW equipped with inertia emulation function the power boost of about 3% of rated power for 5 s is enough to enhance the frequency nadir for 0.07 Hz with the fixed power boost control. This power contribution corresponds to 120 MW of additional net generation for 5 s. Thus, the lowest necessary inertia emulating wind power capacity to reach the same power contribution is in the order of 1000 MW if the power boost percentage is in the order of 10–15% of rated power. Due to the aerodynamic constraints it is not possible to arbitrarily increase the power boost percentage. Namely, 10% of rated power is considered the absolute maximum for the power boost percentage if the power boost duration is 10 s [3][38]. In addition, it was observed that the effect of inertia emulation on the frequency nadir improvement depends on the control method when inertia emulating wind power capacity is increased.

According to the simulations, both of the studied control methods (fixed power boost and proportional power boost) could be parametrized to provide active power support so that the frequency nadir is improved, and the RoCoF as well. However, in the Nordic power system the proportional power boost control seems more recommended than the fixed power boost control since the former adapts to different disturbance events by following the grid frequency and can effectively enhance the damping of the power oscillations during a disturbance event.

In order to evaluate the performance of inertia emulation functionality and to conclude the possible suggestions for the inertia emulation requirement, the research questions described in Section 1.2 are discussed as well.

Availability and limitations of inertia emulation

According to the doctoral thesis of Johan Björnstedt, the inertia emulation function would be available at all the operating points of the power curve (at all wind speeds) to deliver power boost of 10% of the wind turbine generator rated power for 10 seconds [3]. According to the manufacturers contacted by the author, this is true from the electrical side only [38][50]. Namely, there are some restrictions originating from the aerodynamic side as described in Section 3.2.5. Therefore, identifying an explicit operating range for the inertia emulation availability is not possible as it depends on the control method as well as on the power boost percentage and duration. Moreover, the simulations prove that the increase in the energy deficit during the recovery phase is exponential in proportion to the energy delivered during the power boost phase which means that the higher amount of energy is delivered during the power boost phase, the more the risk of a secondary nadir increases.

During the power boost phase of the inertia emulation function the converter apparent power limit can restrict the reactive power output of the wind turbine generator. In the example, the apparent power limit was not met during the power boost phase regardless of the control method. However, one must bear in mind the possibility of the restriction, and therefore, it must also be decided whether to prioritize the active or reactive power during the power boost phase.

One of the most important conditions for setting an inertia emulation requirement is that the same requirement can be formulated for the converter-connected wind turbine generators regardless of the technology they represent. Firstly, it is possible to equip both the Type 3 and 4 wind turbine generators with the inertia emulation function according to the literature and the wind turbine manufacturers contacted by the author. This is considered adequate and reasonable since all the new wind power plants in the Nordic power system are equipped with a converter whereas the other wind turbine generator technologies are not decoupled from the grid through a converter (see [1] for descriptions, for example). Secondly, the operative inertia emulation requirements in Hydro-Québec and IESO's systems concern both technologies. Therefore, there seems not to be any crucial hindrances for setting a common requirement even though some slight differences in their capabilities might appear.

Parametrization of inertia emulation

According to the results of this thesis, the power boost percentage and the power boost duration proved to be the most important inertia emulation parameters. The higher the power boost percentage is, the better the frequency nadir is improved. However, if the energy delivered during the power boost phase is too high, the frequency recovery is significantly delayed or a secondary frequency nadir emerges or both because of the active power drop during the recovery phase. The reasonable power boost percentage therefore depends on the power boost duration but also on the control method and also on the wind power capacity equipped with the inertia emulation function especially when fixed power boost is used. To limit the energy delivered during the power boost phase to a reasonable level, the power boost percentage and power boost duration must be adjusted together.

With the dynamic wind power plant model of Enercon, it is possible adjust the recovery phase characteristics by varying the recovery duration. The changes in the parameter value seemed to work logically only for the fixed power boost control. However, the findings most likely apply also to the proportional power boost control. The simulations proved that the recovery characteristics are crucial for the power system security as it was supposed according to the literature. If the recovery duration is prolonged, the risk of a secondary frequency nadir decreases. The prolonging the recovery duration or the fall time of the power does not however invariably improve the inertia emulation performance. Namely, after a certain point the frequency recovery is unnecessarily delayed. According to the literature, a smooth recovery phase with duration of 20–40 s is recommended in Hydro-Québec's system. This recommendation seems reasonable also in the Nordic power system.

The study indicates that the activation frequency and frequency for maximum power can be utilized in directing the power boost either to improve the RoCoF or the frequency nadir more. Namely, the higher activation frequency is, the better the RoCoF is improved instead of the frequency nadir, and the other way around. This observation is emphasized when inertia emulation is delivered by the proportional power boost control.

Performance of inertia emulation in a power system with power oscillations

As expected, the power oscillations affected differently on the inertia emulation performance when different control methods were used. When the inertia emulation is delivered by fixed power boost, the power oscillations do not influence on the performance of the inertia emulation function. In turn, when inertia emulation is controlled by proportional power boost, the power oscillations are reflected on the power boost through the oscillating frequency signal used in the control. This however seems not to worsen the inertia emulation performance. According to the literature, the utilization of synthetic inertia in a power system with power oscillations requires suitable frequency signal filtering. This naturally applies also to other control methods which control is based on the frequency derivative.

Consistency of inertia emulation with the selected stability criteria

The aim of utilizing the inertia emulation function would be improving the frequency stability of the Nordic power system by improving the frequency nadir reached during severe under-frequency events. However, it would not be practical to require any function that would improve one stability category but weaken another. Therefore, the inertia emulation was studied relative to the different stability criteria. When parametrized and implemented in an appropriate way, the inertia emulation function can improve the frequency stability by improving the frequency nadir and the RoCoF without causing a secondary frequency nadir due to the dramatic active power drop during the recovery phase. Some delay in the frequency recovery is, however, expected due to the recovery phase.

Any remarkable impacts on the voltage stability in the Nordic power system were not observed in the simulations regardless of the control method used. However, some local effects are considered possible but out of the scope of this study.

When the fixed power boost control is used, the inertia emulation does not have influence on the damping of power oscillations either. In turn, when the proportional power boost control is used, the function can effectively improve the damping of power oscillations which is an obvious advantage of the control method. Most importantly, the inertia emulation function does not contradict the stability criteria studied regardless of the control method. Moreover, inertia emulation can even enhance two of the three stability criteria studied if the proportional power boost control is used with a reasonably short delay (0.100 s or shorter) between the frequency measurement and the power control.

Consistency of inertia emulation with fault ride through function

The consistency of the inertia emulation function with the fault ride function depends on whether the activation time of the former and the recovery time of the latter may occur simultaneously or not. As shown in the simulations, contradictions in the functions do not appear when the recovery time of fault ride through is immediate and the activation time of inertia emulation is in the order of 2–4 s. Contradictions may, however, appear if the recovery of the fault ride through function is stretched over some seconds or if the inertia emulation is activated instantly or both.

7.2 Suggestions for requirement setting

It is discovered in this thesis that the inertia emulation functionality has potential in supporting the Nordic power system during severe under-frequency events. This however requires that the inertia emulation function is appropriately implemented and parametrized. Otherwise it is possible that the inertia emulation function could compromise the system stability. In this connection the TSO's responsibility to set the inertia emulation requirement properly and detailed enough is emphasized. The simulation results clearly show that the inertia emulation requirement in the Nordic power system must be more detailed than the requirements operative in Hydro-Québec's and IESO's systems described in Section 4.1.2 and Section 4.1.3. However, these two requirements can be used as a base for the suggestions for the Nordic requirement.

The matters stipulated in Hydro-Québec's and IESO's inertia emulation requirements consist of the following criteria (see Section 3.2.4 and Section 4.1.5 for descriptions):

- control method,
- activation frequency or alternatively frequency dead band,
- maximum power boost rise time,
- minimum power boost percentage,
- minimum power boost duration,
- maximum power drop during the recovery phase,
- availability of the functionality,
- minimum time between consecutive activations.

The principle of the inertia emulation requirement setting in the Nordic power system is that the requirement must be set detailed enough so that, if the requirement is met, the inertia emulation function operates appropriately. Therefore, as highlighted above, the inertia emulation requirement in the Nordic power system should be detailed in order to avoid undesired behavior. Thus, some additional issues are recommended to be covered in the requirement. These issues contain:

- deactivation frequency,
- recovery duration,
- maximum delay between the frequency measurement and the power control,
- maximum power drop gradient during the recovery phase,
- inertia emulation in conjunction with fault ride through
- *df/dt* limit (relevant for power boost proportional to frequency derivative).

Table 18 presents the suggestions for the inertia emulation requirement setting that can be drawn according to this study. Each issue is discussed below.

Table 18. *Suggestions for the inertia emulation requirement setting in the Nordic power system.*

Criteria	**Suggestion**
Objective	To support the power system during large under-frequency events
Availability of the functionality	≥ 25% of rated active power
Control method	Power boost proportional to absolute frequency change or power boost proportional to frequency derivative or combination of the above-mentioned
Maximum delay between frequency measurement and power control	0.1 s
Activation frequency	Between 49.30–49.70 Hz
df/dt limit	(relevant for power boost proportional to frequency derivative)
Power boost rise time	In the order of 0.5–3 s (relevant for fixed power boost)
Power boost percentage	In the order of 10% of rated active power
Power boost duration	In the order of 10 s
Deactivation frequency	49.90 Hz
Maximum power drop during the recovery phase	In the order of 10% of rated active power
Maximum power drop gradient during the recovery phase	In the order of 1% of rated active power per s
Recovery duration	Between 30–60 s
Time between consecutive activations	Blocked until the recovery phase is over and the frequency has been recovered above the activation frequency
Inertia emulation in conjunction with fault ride through	Prioritization of inertia emulation (active power) vs. prioritization of FRT (reactive power)

Firstly, the objective of the inertia emulation function in the Nordic power system would be supporting the system during large under-frequency events. Additionally, the need for inertia emulation function is emphasized at high wind speeds when the share of wind power in the total generation is high. Thus, it is not necessary to require the function to be available at the lowest power output. The function could therefore be required from 25% of rated active power, for example.

The control methods of power boost proportional to frequency change or power boost proportional to frequency derivative or combination of the above-mentioned are suggested to be required. The control methods that are either proportional to the frequency change or frequency derivative or both can improve the damping of the power oscillations and are adaptable to different disturbance events. In this connection, it is however crucial that the delay between frequency measurement and power control does not exceed 0.1 s. Otherwise, the advantage is lost in addition to weakening of the inertia emulation performance. Namely, the ability of power boost proportional to frequency change and frequency derivative to increase the damping depends on the delay between the frequency measurement and the power control.

Since the objective of the inertia emulation function would be supporting the power system during large under-frequency events, the reasonable activation frequency is between 49.30–49.70 Hz. The final recommendation depends on the capability of the inertia emulation to deliver the power boost for desired duration as well as on the power boost percentage. An activation frequency in the order of 49.30 Hz is recommended for function with the power boost duration of 5 s. In turn, if a power boost duration of 10 s is possible, then the activation frequency can be higher. The idea behind the higher activation frequency and the longer power boost duration would be the aim to align the power boost phase with the lowest frequencies reached in the most severe disturbance events. If the control method of power boost proportional to frequency derivative is used, a *df/dt* limit should also be considered for the activation of the function. According to this study, it is not however possible to suggest any specific value for the *df/dt* limit.

The criteria of power boost rise time is only relevant for fixed power boost. The shorter the power boost rise time is, the steeper the power increase is after reaching the activation frequency. As this study indicated, the closer the activation frequency and the frequency for maximum power are, the steeper the power increase is, and the more the RoCoF is improved instead of the frequency nadir though the effect was quite slight. Nevertheless, a recommendation for the power boost rise time after the activation of inertia emulation would be in the order of 0.5–3 s since without inertia emulation the frequency nadir is typically reached between 5–8 s after the beginning of the disturbance. Additionally, the time that it takes until the nadir is reached is typically delayed by the effect of inertia emulation. Again the aim is to align the power contribution of inertia emulation with the lowest frequencies reached.

The power boost percentage and the power boost duration determine the additional energy delivered during the power boost phase. Therefore, it is reasonable to consider them together. According to the simulations, the suggestion for the power boost percentage and duration would be 10% of rated power for 10 s. However, this must be studied further with different implementations of inertia emulation and with different control methods.

Once the inertia emulation function is activated, the function is desired to deactivate before it has delivered the full power contribution only if the frequency recovered exceptionally fast in the normal range of 49.90–50.10 Hz before the power boost duration is exceeded. Since the exceptionally fast recovery of the frequency is far from typical, the impact of deactivation frequency were not simulated in this thesis. However, it is assumed that the deactivation frequency of 49.90–50.00 Hz would be appropriate, and therefore, 49.90 Hz is suggested for the required value of the deactivation frequency.

As the literature survey as well as the simulations proved, the impact of the recovery characteristics on the power system stability cannot be exaggerated. In order to avoid a secondary nadir and to enable smooth recovery characteristics, it is suggested that both the power drop and its gradient should be limited during the recovery phase. For example, it is obvious that a power drop of 10% of rated power can be too dramatic if it occurs in a couple of seconds. For the same reason, the recovery phase should be stretched over a period of time long enough meaning a duration of 30–60 s. According to the simulations, it seems that the maximum acceptable power drop during the recovery phase is in the order of 10% of rated power and the maximum acceptable power drop gradient during the recovery phase is in the order of 1% of rated active power per s. Additional simulations will be required before more accurate suggestions could be stated.

The inertia emulation function should not activate twice during the same disturbance event though the frequency would remain below 49.90 Hz since the frequency containment reserves and frequency restoration reserves are utilized to manage the later phases of the frequency disturbance event. Therefore, the inertia emulation function should be blocked until the recovery phase is over and the frequency has been recovered above the activation frequency.

Finally, it should be decided whether to prioritize the power boost of inertia emulation or the active power recovery after fault ride through operation if the functions are activated simultaneously. Even though the actual fault ride through operation occurs during the fault, it should be noted that the optimal recovery time for the fault ride through function for the wind power plants in the Finnish power system is 2–3 s [48] which means that the recovery of the fault ride through could occur concurrently with the activation of inertia emulation power boost. In other words, it should be decided whether to prioritize the active or reactive power during the simultaneous under-frequency event and a fault causing low voltages locally nearby the fault location.

8. CONCLUSIONS

This chapter describes the conclusions drawn from the results of this thesis. Finally, the suggestions for future work are listed, too.

8.1 Conclusions

Since only one manufacturer-specific wind power plant model was used in this thesis, a following question may arise. Namely, one may question whether it is reasonable to draw system wide conclusions according to the simulations executed with one manufacturer-specific model. The answer depends on the way how the conclusions are drawn and how the results are utilized. In this thesis, the manufacturer-specific wind power plant model is used to analyze the possible weaknesses or problems that may arise if the inertia emulation function is not formulated properly. Thus, the simulations are used to demonstrate the issues that should be taken into account when setting an inertia emulation requirement. Moreover, this study represents only suggestions for the requirement setting and it is also emphasized that additional simulations are needed in order to formulate a precise requirement. The recommendations for future work are discussed below in Section 8.2.

The increasing share of converted-connected generation in the Nordic power system leads to a situation with low power system inertia. Consequently, the frequency deviations in severe faults increase and the risk of exceeding the first step of under-frequency load shedding increases, too. If the present system security level and the frequency stability of the power system are decided to retain, the frequency deviations in the severe faults must be managed to a specific limit. One option to achieve this aim is the inertia emulation capability of converter-connected wind power plants that could be used to support the power system during large under-frequency events.

The technology of inertia emulation is already commercially available but the initial implementations of the function have been designed to meet the inadequate requirements set earlier by Canadian TSOs. Hence, the present inertia emulation functions may require some upgrading in order to meet the more detailed future requirements. For example, according to the literature, the inertia emulation implementation of Senvion with the smooth recovery characteristics seems significantly better than the implementation of Enercon with a dramatic power reduction during the recovery phase. Naturally, Enercon is aware of the weaknesses of the function and is developing especially the recovery characteristics of Constant power increase mode.

The dynamic wind power plant model used in the simulations presented in this thesis proved to have some weaknesses in its inertia emulation functionality. Among them are, for example, the remarkable power reduction during the recovery phase when the fixed power boost control selected and the malfunctioning of the recovery duration parameter when the proportional power boost control selected. The weaknesses in the implementation originate from the immaturity of the function and its modeling. Nevertheless, for the requirement setting point of view it was valuable to use a model with weaknesses because due to the weaknesses some possible issues that otherwise would perhaps not be taken into account were revealed. The suggested criteria of maximum power drop gradient during the recovery phase is an example of this type of finding. Despite the weaknesses it was still possible to find a parameter setting that could improve the frequency nadir detected in the disturbance events studied. This clearly demonstrates the potential of the inertia emulation function.

The study proves that for system security the inertia emulation requirement must be formulated in detail if such functionality was decided to be required. If the requirement is not properly set, the inertia emulation function could compromise the system stability. However, according to the study, the inertia emulation function has potential in supporting the system during under-frequency events when parametrized and implemented in an appropriate way. Moreover, the study did not show any inevitable hindrances that would prevent the Nordic TSOs from setting an inertia emulation requirement in the event that they would decide to do so. Namely, in practice, the inertia emulation function seems not to have any impact on the voltage stability in the Nordic power system, though some local effects are possible but not studied in this thesis. Additionally, the inertia emulation of fixed power boost does not effect on the damping of frequency/power oscillations. Moreover, when activated, the inertia emulation of proportional power boost can effectively improve the damping of frequency/power oscillations. Hence, the proportional power boost control was considered more recommended for the Nordic power system.

The previous research on the topic has focused on the inertia emulation or its control from the theoretical perspective or analyzed the performance and operation of inertia emulation in Hydro-Québec's system. Many of the publications have not analyzed or discussed the performance of inertia emulation from the requirement setting point of view which is the major contribution of this thesis. Namely, some additional criteria for inertia emulation requirement compared with the operative requirements in Hydro-Québec and IESO's systems were found in this thesis. With the extended list of criteria it is easier to formulate a detailed inertia emulation requirement that more certainly ensures the satisfactory inertia emulation performance. Even though the suggestions applies only to the Nordic power system studied in this thesis, the criteria can be useful regardless of the power system.

The ideal inertia emulation functions in comparison to the real implementations of the function may differ from each other significantly and there exist a number of possible variations of the implementations. This naturally underlines the importance of the future studies on the topic as well as the need for detailed requirements by the TSOs.

8.2 Future work

This thesis studied the inertia emulation functionality in the Nordic power system and the effects of the control method and parametrization on the performance of the function. As described in Section 7.1 this thesis achieved this objective by covering the research questions and also revealed some valuable additional findings. However, the information provided in this thesis is not solely adequate for possible inertia emulation requirement setting. Therefore, some recommendations for future work are discussed in this section.

First of all, it would be recommended to execute additional simulations with different manufacturer-specific dynamic models of wind power plants for the sake of comparison. The main control methods of power boost proportional to frequency change and power boost proportional to frequency derivative could be beneficial to study separately as in this thesis only the manufacturer-specific combination of these methods were investigated. Another crucial thing is that all the wind power plants equipped with the inertia emulation function operate at full power in this study. Therefore, studying the effect of the operating point to obtain understanding on the operation and performance of the function in different conditions would also be recommended when executing the additional simulations. Moreover, the additional simulations should also enable analysis on the coordination of inertia emulation and frequency containment reserves for disturbances. It could also be interesting to study the inertia emulation capability in a situation in which the power boost was provided by different control methods at the same time. In other words, some of the wind power plants would provide inertia emulation by fixed power boost, and some would provide inertia emulation by proportional power boost, for example.

After the reasonable additional simulations are executed it is possible to formulate a proposal for the inertia emulation requirement for converter-connected wind power plants. This means that the suggestions presented in this thesis are formulated into a detailed requirement on the grounds of the additional simulations. However, it is reasonable to test the inertia emulation function of a real wind power plant to study whether the simulations and measurements have a good correspondence as well as whether the inertia emulation function can meet the proposed requirement. Hence, a field test is recommended after the proposed inertia emulation requirement is formulated.

There are also some issues that may be useful to analyze in addition to the recommendations described above. In this study, all the wind power plants equipped with the inertia emulation function locate in Finland. Therefore, it would be interesting to study the performance of the inertia emulation and its effect on the system when there is more than 4000 MW wind power capacity equipped with inertia emulation function spread around the Nordic power system. Additionally, as the study showed, the duration of the recovery phase should be long enough in order to avoid a steep power reduction during the inertia emulation recovery phase. Smoother recovery characteristics experienced by the power system may also be achieved by setting the recovery phases in different wind power plants to start gradually at different moments of time. The same idea could also be applied to the parameters determining the behavior during the power boost phase.

REFERENCES

[1] T. Ackermann, Wind Power in Power Systems, 2nd Edition, John Wiley & Sons Ltd, Chichester, United Kingdom, 2012, pp. 906 - 909.

[2] M. Asmine, C.-É. Langlois, N. Aubut, Inertial Response from Wind Power Plants during a Frequency Disturbance on the Hydro-Quebec System - Event Analysis and Validation, Proceedings of the 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, November 2016, 8 p.

[3] J. Björnstedt, Integration of Non-synchronous Generation - Frequency Dynamics, Doctoral dissertation, Lund University, January 2012, 111 p. Available (accessed on 22.10.2017): https://lup.lub.lu.se/search/ws/files/6096394/2536749.pdf

[4] D. Deroost, P. Tielens, D. Van Hertem, K. Srivastava, G. Velotto, Analysis and coordination of delivering inertial response by wind power plants, Proceedings of the 14th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Brussels, October 2015, 6 p.

[5] EirGrid, SEMO & SONI, DS3 System Services: Portfolio Capability Analysis, November 2014, 15 p. Available (accessed on 22.10.2017): http://www.eirgrid.ie/site-files/library/EirGrid/DS3-System-Services-Portfolio-Capability-Analysis.pdf

[6] EirGrid & SONI, Consultation on DS3 System Services Interim Tariffs, April 2016, 27 p. Available (accessed on 22.10.2017): http://www.eirgrid-group.com/site-files/library/EirGrid/OPI_INV_Paper_DS3-Interim-Tariffs-Consultation-FINAL-08042016.pdf

[7] EirGrid & SONI, DS3 RoCoF Alternative Solutions Project Report Overview, March 2016, 7 p. Available (accessed on 22.10.2017): http://www.eirgrid-group.com/site-files/library/EirGrid/DS3-RoCoF-Alternatives-Solutions-Project-Phase-2-Overview-Final.pdf

[8] ENERCON GmbH, ENERCON wind energy converters: Technology & Service, June 2015, 23 p. Available (accessed on 22.10.2017): https://www.enercon.de/fileadmin/Redakteur/Medien-Portal/broschueren/pdf/en/ENERCON_TuS_en_06_2015.pdf

[9] ENERCON GmbH, Technical Description: ENERCON FCU Model EFCU07 for PSS®E, July 2015, unpublished document, 20 p.

[10] ENERCON GmbH, Technical Description: ENERCON Wind Energy Converters Inertia Emulation FACTS 1.1, June 2017, unpublished document, 10 p.

[11] ENERCON GmbH, Technical Description: PSS®E Model ExS3 for ENERCON Wind Energy Converters Release 2.0, October 2014, unpublished document, 27 p.

[12] Energinet.dk, Fingrid, Statnett & Svenska kraftnät, Challenges and Opportunities for the Nordic Power System, August 2016, 65 p. Available (accessed on 22.10.2017): http://www.fingrid.fi/fi/ajankohtaista/Ajankohtaista%20liitteet/Ajankohtaisten%20liitteet/2016/Report%20Challenges%20and%20Opportunities%20for%20the%20Nordic%20Power%20System.pdf

[13] S. Engelken, A. Mendonca, M. Fischer, Inertial Response with Improved Variable Recovery Behaviour Provided by Type 4 Wind Turbines, Proceedings of the 14th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Brussels, October 2015, 6 p.

[14] ENTSO-E, Appendix 1 of System Operation Agreement: Definitions, June 2016, 10 p. Available (accessed on 22.10.2017): https://www.entsoe.eu/Documents/Publications/SOC/Nordic/System_Operation_Agreement_appendices%28English_2016_update%29.pdf

[15] ENTSO-E, Appendix 2 of System Operation Agreement: Operational security standards, June 2016, 8 p. Available (accessed on 22.10.2017): https://www.entsoe.eu/Documents/Publications/SOC/Nordic/System_Operation_Agreement_appendices%28English_2016_update%29.pdf

[16] ENTSO-E, Future System Inertia - Report, 2015, 58 p. Available (accessed on 22.10.2017): https://www.entsoe.eu/Documents/Publications/SOC/Nordic/Nordic_report_Future_System_Inertia.pdf

[17] ENTSO-E, Interconnected network of Northern Europe 2015, website. Available (accessed on 22.10.2017): https://www.entsoe.eu/publications/order-maps-and-publications/electronic-grid-maps/Pages/default.aspx

[18] R. Eriksson, N. Modig, K. Elkington, Synthetic Inertia versus Fast Frequency Response: a Definition, Proceedings of the 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, November 2016, 7 p.

[19] European Commission, Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators

(Text with EEA relevance), April 2016, 68 p. Available (accessed on 22.10.2017): http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:JOL_2016_112_R_0001

[20] European Commission, Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (Text with EEA relevance), August 2017, 120 p. Available (accessed on 22.10.2017): http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017R1485

[21] Fingrid Oyj, Application instruction for the maintenance of frequency controlled reserves, Appendix 2 to the Yearly Agreement and Hourly Market Agreement for Frequency Controlled Normal Operation Reserve and Frequency Controlled Disturbance Reserve, unofficial translation, January 2017, 15 p. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/powersystem/Power%20system%20attachments/2017/Liite2%20-%20Taajuusohjattujen%20reservien%20ylläpidon%20sovellusohje%202017_eng.pdf

[22] Fingrid Oyj, Frequency containment reserves, website. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/electricity-market/reserves/reserve-types/containment/Pages/default.aspx

[23] Fingrid Oyj, Frequency control processes, website. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/electricity-market/reserves/reserve-types/Pages/default.aspx

[24] Fingrid Oyj, Frequency quality analysis 2016, September 2017, 132 p.

[25] Fingrid Oyj, Frequency quality analysis for year 2015, August 2016, 91 p.

[26] Fingrid Oyj, Maintaining of system security, website. Available (accessed 22.10.2017): http://www.fingrid.fi/en/powersystem/Power%20system%20management/Maintaining%20of%20system%20security/Pages/default.aspx

[27] Fingrid Oyj, Maintenance of power balance, website. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/powersystem/Power%20system%20management/Maintaining%20of%20balance%20between%20electricity%20consumption%20and%20production/Pages/default.aspx

[28] Fingrid Oyj, Nordic power system and interconnections with other systems, website. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/powersystem/general%20description/Nordic%20power%20system%20and%20interconnections%20with%20other%20systems/Pages/default.aspx

[29] Fingrid Oyj, Power Transmission Grid, website. Available (accessed on 22.10.2017): http://www.fingrid.fi/EN/COMPANY/COMPANY/POWER-TRANSMISSIONGRID/Pages/default.aspx

[30] Fingrid Oyj, Reserves, website. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/electricity-market/reserves/Pages/default.aspx

[31] Fingrid Oyj, Rules and fees for the hourly market of frequency, Appendix 3 to the Hourly Market Agreement for Frequency Controlled Normal Operation Reserve and Frequency Controlled Disturbance Reserve, unofficial translation, January 2017, 6 p. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/powersystem/Power%20system%20attachments/2017/Liite3%20-%20Taajuusohjattujen%20reservien%20ylläpidon%20tuntimarkkinasäännöt%202017_eng.pdf

[32] Fingrid Oyj, Specifications for the Operational Performance of Power Generating Facilities VJV2013 (unofficial translation), September 2013, 86 p. Available (accessed on 22.10.2017): http://www.fingrid.fi/en/customers/connection/Specifications/Pages/default.aspx

[33] Fingrid Oyj, Voimalaitosten järjestelmätekniset vaatimukset VJV2013, September 2013, 78 p. Available (accessed on 22.10.2017): http://www.fingrid.fi/fi/asiakkaat/liittyminen/teknisetvaatimukset/Sivut/default.aspx

[34] Fingrid Oyj & Svenska kraftnät, Cross-border capacity study between Finland and Sweden, 2016, 85 p. Available (accessed on 22.10.2017): http://www.fingrid.fi/fi/verkkohankkeet/voimajohtoliitteet/Cross-border%20capacity%20study%20btw%20Finland%20and%20Sweden.pdf

[35] Finnish Statistics, Volume of electricity produced with renewable energy sources at record level, website. Available (accessed on 22.10.2017): http://www.stat.fi/til/salatuo/2015/salatuo_2015_2016-11-02_tie_001_en.html

[36] M. Fischer, S. Engelken, N. Mihov, A. Mendonca, Operational Experience with Inertial Response Provided by the Type 4 Wind Turbines, Proceedings of the 13th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Berlin, November 2014, 6 p.

[37] General Electric (K. Clark, N. W. Miller, J. J. Sanchez-Gasca), Modeling of GE Wind Turbine-Generators for Grid Studies, April 2016, 92 p. Available (accessed on 22.10.2017): https://www.researchgate.net/profile/Kara_Clark/publication/267218696_Modeling_of_GE_Wind_Turbine-Generators_for_Grid_Studies_Prepared_by/links/566ef77308ae4d4dc8f861ef/Modeling-of-GE-Wind-Turbine-Generators-for-Grid-Studies-Prepared-by.pdf

[38] N. Hamann, Nordex Energy GmbH. Email dialogue on 17.8.2017–23.8.2017.

[39] Hydro-Québec TransÉnergie, Exigences techniques de raccordement de centrales au réseau de transport d'Hydro-Québec, December 2012, 89 p. Available (accessed on 22.10.2017): http://publicsde.regie-energie.qc.ca/projets/208/DocPrj/R-3830-2012-B-0044-DemAmend-PieceRev-2013_11_29.pdf

[40] Hydro-Québec TransÉnergie, Transmission Provider Technical Requirements for Connection of Power Plants to the Hydro-Québec Transmission System, February 2009, 66 p. Available (accessed on 22.10.2017): http://www.hydroquebec.com/transenergie/fr/commerce/pdf/exigence_raccordement_fev_09_en.pdf

[41] IESO, LRP I RFP Backgrounder - Connection, 2015, 18 p.

[42] IESO, Market Rules: Chapter 4 Grid Connection Requirements - Appendices, September 2015, 61 p.

[43] IESO, Part 2.20: Performance Validation, June 2017, 49 p.

[44] D. Kothari, I. Nagrath, Modern Power System Analysis, 3rd Edition, Tata McGraw-Hill Publishing Company Limited, New Delhi, 2003, 694 p.

[45] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, V. Vittal, Definition and Classification of Power System Stability, IEEE Transactions on Power Systems, Vol. 19, No. 2, May 2004, pp. 1387-1401. Available (accessed on 22.10.2017): http://ieeexplore.ieee.org/document/1318675/

[46] P. Kundur, Power System Stability and Control, McGraw-Hill, New York, 1994, 1176 p.

[47] R. Leelaruji, M. Bollen, Synthetic inertia to improve frequency and how often it is needed Report 2015:224, Energiforsk AB, September 2015, 66 p. Available (accessed on 22.10.2017): https://energiforskmedia.blob.core.windows.net/media/21406/synthetic-inertia-to-improve-frequency-stability-and-how-often-it-is-needen-energiforskrapport-2015-224.pdf

[48] J. Majuri, The Impact of Fault Current Contribution from Converter Based Power Plants on Power System Stability, Aalto University School of Electrical Engineering, Department of Electrical Engineering and Automation, November 2016, 95 p. Available (accessed on 22.10.2017): https://aaltodoc.aalto.fi/handle/123456789/23916

[49] Nordex & ACCIONA Windpower, 360°, Issue 2, 2017, 12 p. Available (accessed on 22.10.2017): http://www.nordex-online.com/fileadmin/MEDIA/Kundenzeitschrift/EN/Nordex-Acciona_360-Special-2017_en.pdf

[50] R. Ogiewa, M. Eng., Sales – Grid Integration Engineer, ENERCON GmbH. Email dialogue on 8.9.2017–27.9.2017.

[51] M. Persson, Frequency Response by Wind Farms in Islanded Power Systems with High Wind Power Penetration, Chalmers University of Technology, February 2015, 112 p. Available (accessed on 22.10.2017): http://publications.lib.chalmers.se/records/fulltext/214090/214090.pdf

[52] L. Shang, J. Hu, Z. Yuan, Y. Chi, Understanding Inertial Response of Variable-Speed Wind Turbines by Defined Internal Potential Vector, MDPI, Energies, Vol. 10(1), No. 22, December 2016, 17 p. Available (accessed on 22.10.2017): http://www.mdpi.com/1996-1073/10/1/22

[53] Statistics Norway, Generation, imports, exports and consumption of electricity, website. Available (accessed on 22.10.2017): https://www.ssb.no/en/energi-og-industri/statistikker/elektrisitet/aar

[54] Statistics Sweden, Electricity supply and use 2001–2015 (GWh), website. Available (accessed on 22.10.2017): http://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/energy-supply-and-use/annual-energy-statistics-electricity-gas-and-district-heating/pong/tables-and-graphs/electricity-supply-and-use-20012015-gwh/

[55] K. Uhlen, M. Pálsson, T. R. Time, Ø. Kirkeluten, J. O. Gredje, Raising Stability Limits in the Nordic Power Transmission System, 14th Power Systems Computation Conference (PSCC), Sevilla, June 2002, 7 p. Available (accessed on 22.10.2017): https://www.researchgate.net/publication/229012973_Raising_stability_limits_in_the_Nordic_power_transmission_system

[56] S. Uski, Wind Power Plant Model Collection Network Representation in an Aggregated Wind Power Plant Model, Proceedings of the 13th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, November 2014, Berlin, 5 p. Available (accessed on 22.10.2017): http://www.vtt.fi/inf/julkaisut/muut/2015/OA-Wind_power_plant_model.pdf

[57] D. Wall, E. Lindström, J. Persson, A Novel Approach for Studying Possibilities with Synthetic Inertia from Wind Power Plants, Proceedings of the 14th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Brussels, October 2015, 6 p.